NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Memorandum 33-543

Proceedings of the Jupiter Radiation Belt Workshop

Held at the Jet Propulsion Laboratory
Pasadena, California
July 13-15, 1971

Edited by
Andrew J. Beck

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CALIFORNIA INSTITUTE OF TECHNOLOGY
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FOREWORD

During the Thermoelectric Outer Planets Spacecraft (TOPS) Study, a design environment for the Jupiter trapped radiation belt was compiled from the existing models. The resulting requirements were imposed on the TOPS system design studies. As a result of this effort, two facts were apparent: first, the uncertainty in the energetic proton and electron trapped radiation models was very large and second, the resulting radiation environment had a strong impact on the TOPS spacecraft design concepts.

In addition, independent Jupiter orbiter and Jupiter probe mission studies showed a similar strong impact of the radiation environment on these spacecraft systems and science complements. Some reductions in the radiation levels could be achieved for fly-by missions by increasing the closest approach distance. However, for missions employing Jupiter for gravity assist, the range of closest approach distances is fixed by the mission requirements and, for orbiters, increasing the periapsis distance requires an increase in the propulsion system energy for injection.

These outer planet mission studies emphasized the need to reduce the uncertainty in the Jupiter trapped radiation belt models and the requirement to establish the best models from which the design requirements should be derived. The best models should be conservative enough that spacecraft designed to the models have an acceptable risk associated with the models, but not so overly conservative that a large design penalty is required for a small reduction in risk. Because of the highly specialized nature of the topic, the questions could best be addressed by a group of specialists who actually were working in the fields involved. Consequently, a group of scientists and engineers met for a JPL workshop on July 13, 14, and 15 1971, to review the current state of Jupiter radiation belt knowledge and to recommend a best set of models for the determination of spacecraft design requirements. This workshop was organized and conducted by the Project Engineering Division for the Outer Planets Project of the Jet Propulsion Laboratory.

This Proceedings contains the papers with the discussion that followed in the order that they were presented at the workshop. Thus, the Proceedings has the same general organization as the Workshop agenda:

I. Jupiter Radiation Belt Models
II. Radiation Effects
III. Recent Earth-Based Observations
IV. Theoretical Considerations
V. Pioneer F and G
VI. Summary

Each participant was invited to present a paper related to one of these topics. Following each presentation, adequate time was scheduled to allow an in-depth discussion by the entire group. The papers and the discussion are in the form as they were received and reviewed by the contributors. Thus, the papers and the discussion represent the expressed views of the participants.

The entire group formulated the recommended set of models and discussed the assumptions on which they are based. In this respect, it should be pointed out that any number of probably equally good models based on various assumptions related to source mechanism, acceleration mechanisms, and loss mechanisms could have been postulated. However, two thoughts were in the forefront: 1) to keep the models spacecraft design orientated and 2) to establish a best nominal model and a lowest possible upper limit model for the trapped energetic electrons and protons. The recommended models are intended to meet these requirements. However, when in situ measurements of the trapped protons and electrons are made by Pioneer spacecraft in 1973 and 1974, there may be some real surprises in the data returned.

As editors, we wrote the initial version of the Conclusions and edited the discussion which led to it. However, both should be credited to everyone who attended the Workshop. The contributions of the participants provided the end results, and their comments and criticisms led to the final version presented here. Thus, the models presented in the Conclusion represents the compromised view of all the participants as to what constitutes best estimates.

In this respect, perhaps it should be emphasized that several groups continued the investigation of the models after the Workshop, and as a result of this continued effort, the revision of some specific details of the models have been required. However, these revisions have been reviewed by the entire group of participants.

Two important papers presented at the Workshop were not available to the Proceedings at the time it went to press. One was a paper by Dr. Wilmot Hess, dealing with the effects of Jupiter's moons on the trapped radiation belt and the second, by Dr. Stephen White, dealing with CRAND as a source for protons trapped in the Jupiter magnetosphere. Hopefully, these papers will be published in the open literature in the near future.

ACKNOWLEDGEMENT

From the conception of the Jupiter Radiation Belt Workshop to the publication of the Proceedings, numerous people have contributed to organizing and conducting the Workshop and to preparing these papers for publication. I would like to express my appreciation to all who contributed to the success of the conference. In particular, the participants at the conference have taken time out of their busy schedules to prepare, deliver, edit, and proof-read the individual papers as well as the discussions. For this assistance I am indeed grateful. In addition, I would like to thank Neil Divine for his help during the organization and conduct of the Workshop as well as editing and proof-reading parts of these Proceedings. Finally, Nancy Boyd was indispensable in typing and preparing the photo-ready copy of these Proceedings for publication.

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WELCOMING REMARKS

Harris M. Schurmeier, OPGT Project Manager
Jet Propulsion Laboratory

On behalf of JPL and NASA, I would like to welcome you to JPL for the Jupiter Radiation Belt Workshop. We believe that this workshop is a very important activity, and expect that the results will influence mission design as well as spacecraft design for some time to come.

The Jupiter environment is, of course, a key constraint to spacecraft designed for missions to Jupiter or to the outer planets using Jupiter for gravity assist. Electrons and protons which may be trapped by the Jupiter magnetic field can potentially produce permanent radiation damage in some instruments and equipment as well as unacceptable interference in others. Consequently, it may have a significant effect on grand-tour spacecraft, Jupiter orbiter spacecraft, and Jupiter swing-by spacecraft. Because Pioneer F and G spacecraft will fly by Jupiter, this environment is a key constraint, I think, for these spacecraft.

One prime purpose of the Pioneer F and G missions is to make in-situ measurements in the Jupiter magnetosphere. Radiation detectors are designed to measure energy distribution and flux for both the electron and proton populations. The design of the mission as well as the experiments are based on a current understanding of the radiation belts. Therefore, the results that come out of this workshop could have some impact, in fact, on the mission profiles for the two Pioneer flights.

To design an outer planets mission spacecraft, we, in the Project Office, must establish radiation design levels and, as a first step toward establishing these levels, we are asking your assistance by helping us to make the best possible estimate of this environment. Clearly, if we are too pessimistic which is, of course, the easy way out--that is, if we are very conservative and therefore design everything to very conservative levels--the spacecraft design would be very expensive and the mission return would be very much compromised. On the other hand, if we are too optimistic--that is, if we say it is a very minor environment and ignore the problem--then we would get severe instrument and spacecraft equipment degradation or failure and would not achieve a successful mission.

Consequently, we must establish design requirements that are based on the best estimate that can be made for the Jupiter radiation belts. And to this extent I would like to emphasize the importance of the summary session on Thursday afternoon. The end result is not obtained until we put all this together and establish the trapped radiation belt models which we can use to establish spacecraft, instrument, and mission design requirements.

Finally, I would like to thank all of you in advance for attending this workshop and for working as hard as you will for the next three days.

Thank you.

A MODEL FOR JUPITER'S PROTON RADIATION BELT

James Warwick*

It may be that of the people in this room, I'm the only one that's already prepared his paper. It's a contractor report[1] that I've prepared at the request of Neil Divine and Andy Beck two years ago. It's both an embarrassment and a pleasure not to have to prepare another document. I wouldn't change too many of the details if I were asked to do it today.

It has a disadvantage that I have led with my chin, so to speak, and it is for all of you to criticize that in whatever detail you wish and improve the estimates of proton and electron densities that are contained in this document. The reason for an estimate of protons--for which there are no experimental data, to the best of my knowledge--is essentially that Neil and Andy are pushy people, you know--very pleasant, but they won't let you get away without giving them the numbers that they have said they need. Two years ago, when I came out here in June, it was just that situation. For six weeks, I told Neil there is no way to estimate protons in Jupiter's radiation belts, and he said, "If you don't, we will, and we think you can do it better than we can." Well, I suspect the reason for this conference is just that. One person, namely I, has stuck his neck out, not with any feeling that he has prior claims to the field or better insight than anybody else, but this is a basis from which to start, and perhaps you all collectively can do better than I can individually.

The logic of the proton densities and electron densities that are reported here I think I will review just verbally. We observe the synchrotron emission from Jupiter's energetic electrons, and questions on how that will be interpreted have been handled differently by different people. I don't know that anyone else has handled that problem of interpreting energetic

*University of Colorado, Boulder, Colorado 80302

[1] Warwick, James W., Particles and Fields Near Jupiter, Report CR-1685, NASA, 1970

electrons in Jupiter's belts, the way I have. I have estimated the surface brightness of the electron emission from Jupiter's radiation belts from the data of Branson. These were aperture synthesis data taken from a large collecting area over a period of time, and the data were published in the form of brightness temperature contours defining the well-known outlines of Jupiter's radiation belts. I used a set of formula to deduce electron densities from the brightness temperature, which are also non-traditional, rule-of-thumb formulas. They scale correctly with respect to the parameters of energy and magnetic field strength, but they are not the classical formulas that appear in the literature for synchrotron emission.

My reasons for doing that are twofold. The first is that the formulas I present are approximately correct even compared to the standard formulas, but the second reason is that the standards themselves, as has been abundantly shown over the last five years, are currently subject to revision. They are not stable, well-defined formulas.

I think I can state one point that will perhaps generate more discussion than it will light, but I will make the comment anyway in a heuristic sense. Swinger's famous derivation in 1949 defines the power spectrum of the total power emitted by electrons in a circular orbit around the magnetic field. This formula, nevertheless, has been used to deconvolve energy spectra of electrons, for which it's clearly inappropriate. We don't observe the total power emitted from a given electron. What we observe is the electric field from a given electron whose beam pattern in space swings through a wide volume above us, and the pattern with which that beam cuts through us determines the spectrum of the emission that we see from the electron, not the total power emitted into all directions.

I don't make apologies for those formulas. They are simple. They give the right scaling with respect to the various parameters, and the numerical coefficients are approximately correct, as well.

We interpret brightness temperature by a formula which gives the intensity in terms of electron energy, electron density, pitch angle, field strength, path length, and so on, and out of that interpretation comes a density for relativistic electrons at the peak of Jupiter's radiation belts. We have to know what the energy of the electrons are. That is convolved with the magnetic field strength. I have taken the magnetic field strength from the model that I published for Jupiter's magnetic field. There is no magic in that model. This technique eliminates an order of magnitude of uncertainty that results from magnetic field measurements or estimates made exclusively from the synchrotron radiation.

The model I proposed depends on a decametric, that is to say, a low-frequency, nonthermal emission model that is, as you well know, highly equivocal. The model, however, does put the field strength in the middle of the range derived strictly from the synchrotron emission, and I think that that is a virtue--whether it's a confirmation or not, I don't know. But out of that, then, comes an energy--a characteristic energy--for the electrons. The energy that I have computed within the green book[1] lies in the range of three to six million electron volts for electrons.

I have not derived a spectrum in this model. I do not believe that up until the time this was written there were observations which permitted to derive a model of the spectrum of the electrons, as I will state in a moment. I think there are brand-new data, as yet unpublished, which do permit an estimate of the electron energy spectrum. Fortunately, it is the same spectrum that people have been talking about on the basis of inadequate data for the last ten years, so I'll mention that in a moment.

We do have an electron density and an energy, and the question now is can we go further with that along the lines of extending it in space away from the peak of the synchrotron belts and in the sense of perhaps inferring a little bit of the dynamics of these electrons, what their source is, and what their lifetimes are. The lifetime, incidentally, for three to six MeV electrons in a field of the order of one gauss is rather short--a fraction of a year, several months--and I think that this also perhaps sets this model aside from other models that have been proposed. Whether you like such short lifetimes or not is perhaps a matter of taste. There are some fragile data which say that the lifetimes may be that short.

We have an electron density peak, and what we're going to do with it is scale it, if you will, out through Jupiter's radiation belts on the assumption that these electrons originate in the general solar wind pattern that flows past Jupiter. Again, there are alternates that have been proposed. One could suppose that the electrons are from the cosmic ray albedo source which would be energetic protons that strike the atmosphere and create neutrons which decay en route through the magnetic field of Jupiter. At least in the early days it was felt that the model was inadequate. If I read the agenda correctly, we may hear more discussion on that later, so I won't go into it.

In any case, the model I propose starts by assuming that the electrons come from the solar wind and use an explicit model for the energy that the electrons acquire as they diffuse in from the solar wind and for the density distribution. This is a schematic model, in a sense. We can regard it as an interpolation formula, if you will. If you assume that the electrons are coming from the solar wind, then any appropriate interpolation model should work, since we know the density in close to Jupiter and the density at the solar wind.

Well, that isn't quite what I did. I've used the Davis and Chang diffusion model in which there is a very steep L-shell dependence in density and energy, and scaled that outwards from the peak of the belts at about 1.5 to 2 Jupiter radii to the magnetopause at Jupiter radii as defined by the magnetic moment that I referred to a few minutes ago. At that point it turns out the density of the energetic electrons is about one billionth that of the solar wind. So, I make the assumption that this is the trapping ratio, that is to say, of the electrons which are in the solar wind and which will eventually diffuse in to become the energetic electrons in the peak of Jupiter's synchrotron belts, to the total solar wind electron density. One electron in one billion from the solar wind goes through that process.

At this point, I was perfectly happy to stop the study, but, as I said, Neil wouldn't let me stop it, and the question was, "What shall we do about the protons?" So I have said--completely arbitrarily so far as I am concerned--that the trapping ratio for protons is precisely the same as for electrons and that they diffuse in according to the same interpolation formulas, if you will, as the electrons do. That simplifies the computation, obviously. Whether it's correct or not is something perhaps we'll have as the major topic of this conference. In any case, it gives a model for the protons in Jupiter's radiation belt;one proton in one billion is trapped at the boundary of Jupiter's magnetosphere and diffuses in to become the energetic proton component of Jupiter's radiation belts.

The numbers are all in CR-1685! As I said, I won't write them down again. They are apparently frightening. I say apparently, not because I feel snobbish about these things, but I'm a radioastronomer who works on the surface of the Earth and has not, up until now, felt compelled to get involved with the space program, but people who are competent in this area tell me that the fluxes that result from this kind of a computation are deadly serious insofar as the survival of all sorts of spacecraft components are concerned, and I accept their word.

There are new experimental results since this report. One in particular that you may not have been aware of is 80MHz observations of Jupiter by the Culgoora ring array near Sydney, Australia. This is Paul Wild's imaging radiotelescope, used primarily for studies of the sun, but consisting of about a hundred forty-foot dishes with very considerable collecting area. They produce angularly-resolved picutres of solar radio bursts, and those are very interesting in their own light.

The flux for Jupiter at 80MHz is a sometime thing. Up until the time the Culgoora ring looked at it, there have been a number of attempts to observe Jupiter at 80MHz, but with rather poor signal-to-noise ratio. Still, the Culgoora ring has not achieved optimum resolution nor ideal signal-to-noise ratio on the 80MHz radiation, but it measures the flux density accurately. And it turns out that at 80MHz, the flux density is identical to what it is at 3,000MHz.

Now, I said earlier that that is a very decisive fact so far as the spectrum of the electrons are concerned and, in my opinion, is the first measurement which is decisive in that respect. The synchrotron bandwidth is extremely broad. I've used the factor of 10 times the peak frequency in this document to define synchrotron bandwidth; there is a certain arbitrariness in the way you're going to define the bandwidth. But, in any case, it's clear that it's broad, so if one is observing at 1400MHz, it really doesn't produce a separate data point from, say, an observation at 600MHz, even on the most conservative estimates of the synchrotron bandwidths. On the other hand, we're now talking about 80MHz, and so it can be said, I think, correctly, that the synchrotron source has constant flux density over something like 20 or 30 to 1 in frequency, which is much broader than the synchrotron characteristic bandwidth, and therefore is telling us something about the energetic electron spectra.

There are other possibilities of convolution here, such as the spatial and pitch-angle distribution of the electrons. I wouldn't really try to deconvolve all that. I think in principle it is an extremely difficult problem, but I think with this new and well-defined low frequency point, it is safe to say that the synchrotron spectrum is flat over considerably more than an order of magnitude of frequency.

The implications for electron spectrum are quite important. It means that the differential spectrum of electron energies is going as E to the minus 1 down to electron energies considerably less than those reported in this document.

The publication will be by Slee and Dulk, and it will appear, I think, in the Australian Astronomical Journal.

I said earlier that that spectrum had been suggested widely in the literature earlier for the last ten years, in fact, but on the basis of a limited frequency of range of observations. I think at this point, if you will, it confirms the earlier hypothesis on the spectrum and does imply a rich low-energy electron spectrum.

I'd like to make a couple of final points and then get off the stand, because, as I said, I've already put down in writing whatever may be my good thoughts on the matter. The reason that these numbers for protons come out high are not magical. It's possible for anybody to, I think, easily comprehend the logic that's involved. The basic reason is that Jupiter is an enormous synchrotron source, and the magnetic field of Jupiter is strong. We have those two components of the argument which appear to me to be inescapable.

In talks about the subject as a prelude to this conference, several of us in this room here have discussed possible reasons why the proton estimate could be wrong, and I would like at this point to get my licks in on that. The electrons that we see are at one or two Jupiter radii from the surface of Jupiter. No matter what the driving force of the diffusion is for the moment, if they have diffused in from the magnetopause, the satellite hazard has obviously somehow been circumvented by these electrons. We might make a distinction between the electrons and the protons so far as satellite trappings are concerned. It seems to me that therefore, the reasons that the electrons are there have to be looked at very closely, and I hope we will look at it closely during this meeting.

I think something else is obvious, and that is in some scaling aspects, the Jupiter radiation belts are very different from the Earth's, for example, in the drift times. Neil Brice can tell us in detail about this. At least, I've seen manuscripts from him which discuss the diffusion times for electrons in Jupiter's magnetosphere. They're very long diffusion times, and the reasons, again, are the strong magnetic field. The fact is, Jupiter is exposed to the same solar wind as is the Earth, or at least we have to assume that in the absence of other information. The steps that the electrons go through as they come in get smaller and smaller the closer they get to Jupiter, but the rate at which the steps occur is the same--a few per day if it's like the Earth. And you just don't do much good so far as diffusion is concerned in terms of the time scales that you need, which suggests that something else is driving the diffusion, and I don't have a suggestion for what that something else might be.

I do have a feeling for the satellite interaction phenomena which may be useful. I have looked at the way some particles might get around the satellites--and the satellites are sitting there lethal as can be waiting to trap the electrons and obviously the protons, as well. You can look at several techniques for avoiding the satellites. The one I have tried to look at--and so far not in enough detail to justify my reporting it--is the possibility that the particles are scattered, so to speak, around the satellites by the magnetic perturbations that the satellites themselves create.

The strength of that kind of a proposition will obviously finally be that the magnetic perturbations are sufficient to scatter particles around, but the initial strength of that kind of a hypothesis is, first of all, that the electrons do get around, and, secondly, that the satellites obviously are magnetically linked to Jupiter. In other words, the region of space, at least from Io to Jupiter, has an Io-created disturbance in it. I think that it is not a remote possibility--I think it is quite obviously a first-order priority--to compute what the effects of that magnetic disturbance might be on the particle orbits--the energetic particle orbits. I have made a preliminary attempt at that, as I say. It is nothing that I want to report here, since I simply don't believe even the first numbers that I've put down, but it's something for those of you who are concerned with this problem to spend time on.

DISCUSSION

DR. BEARD: I wonder if the synchrotron emission is as flat as what these measurements that you've discussed would suggest? As you know, the disk temperature at the shorter wavelengths--since the emission is the disk temperature times the frequency--the disk temperature at the shorter wavelengths in the work that we're presently trying to analyze seems to completely dominate a good part of the spatially-resolved measurements. In other words, the flux that you're observing from the disk is as much or more at some wavelengths as the flux that you're observing from the nonthermal radiation, and therefore, at the shorter wavelengths, the nonthermal radiation is not as great as the fact that a constant flux over all the spectrum of zero spectral index would seem to indicate.

DR. WARWICK: I could comment on that. I have used as more or less a rule-of-thumb that at 10 centimeters--3,000MHz--something like 10 or 20 percent of the total flux is in the thermal flux, from the disk of the planet. Glenn Berge will probably have comments to make on that. But that would be at 3,000MHz. If we go to 2,000MHz or still lower frequencies, the thermal component is dropping very rapidly as the square of the wavelength, so my assumption has been that by 2,000MHz, the flux is entirely nonthermal, so that the strength of the point at 80MHz is to have given a 30 to 1 or 25 to 1 frequency range of flat flux. At the time, we had solid flux measurements only at 400 or 500MHz, then that would have been in band with the four or five, and it was entirely conceivable that it was not flat.

Perhaps I'm stressing too much this 80MHz datum, but I mean I was prepared to think it was just another measurement confirming a flat flux, but then I began to think a bit about the implications, and it seemed to me that it did provide exactly what you are, I think, correctly feeling insecure about--mainly, that the flux, indeed, is really flat over that range.

DR. GULKIS: A more important question is what is the spatial extent of the 80MHz observations, because if it is different than higher frequency observations, then the spectrum may be very much different.

DR. WARWICK: Yes. I tried to stress that point in this document! Sam (Gulkis) and I have talked about it frequently. The question is what would interferometry as a function of frequency look like, and we all recognize that an extended source at low frequencies really makes the whole picture completely different than we've discussed here.

If there is an extended source at low frequencies, such as McAdam*suggested, for example, then these numbers are almost meaningless, because the amount of electrons in these weak magnetic fields and extended regions that are required to produce the observed fluxes are simply fantastic. I think I've stressed that point here. I won't really develop it more.

*McAdam, W.B., 1966, Planetary and Space Sci. 14, 1041.

DR. BEARD: I haven't finished analyzing our recent computer output--but looking at it just qualitatively without examining it yet, it seems that at 10 centimeters, the disk emission is a lot more than just 10 or 20 percent.

DR. WARWICK: That may be. It wouldn't change the hypothesis.

DR. BERGE: I could give you the number. At 10 centimeters, it's about 30 percent, almost exactly one third of the total.

DR. BEARD: I think we might get a little more than that from the computer.

DR. GULKIS: On what basis?

DR. BEARD: Well, I'm hoping it will work, if Glenn can help me out. I'll discuss this in my talk tomorrow, but what I did was to take an inverse Fourier transform of one of your drafts, and I didn't know the phase factor.

DR. WARWICK: Incidentally, one more point about the Australian result. The imaging telescope does not have sufficient resolution to give spatial detail at 80MHz. I think it's a 1.6 minute of arc beam, and it's just not sharp enough to see the distended source. We could say that that puts a rather poor upper limit on the difference in size that might evolve as we went to lower frequencies. Let me say that again. At lower frequencies, we perhaps might expect an extended source. If so, the upper limit of that source size is rather too large to be useful on the basis of the 80MHz ring.

DR. CARR: Are they trying to look for fluctuations at that frequency--possible temporal fluctuations?

DR. WARWICK: Yes. But they can't find any in the run of data they had.

DR. KENNEL: How many data did they actually look at?

DR. WARWICK: They looked at a thousand different data terms, that is to say, flux density determinations. It's a lot of data over a period of time covering about a year.

DR. LIEMOHN: Do you have any additional data on the magnetic fields, distortion, displacement, from the centroid--tilt, and so forth?

DR. WARWICK: A couple of comments on that. I should have mentioned this as I went along. There has been a measurement of optical circularly-polarized emission from Jupiter.* That is to say, in optical wavelengths, there's been a circularly-polarized analyzer used to look at the light, and about one part in 10^5 of the light is circularly polarized. The person who did this was Kemp and his associates, who discovered the circular polarization in white dwarf light and interpreted that observation as a result of a magnetic field of 10^7 gauss.

If you use the same formulas that they use for the white dwarfs for Jupiter, what you get is a field of 10^3 to 10^4 gauss--the field more or less scales as the percent polarization. The White Dwarf was stronger polarized, and Jupiter is extremely weakly polarized. The theoretical basis for this is the splitting of the continuous opacity in the presence of a magnetic field, and it takes a big field to split the opacity enough on its frequency scale to give a difference in optical depths in the two states of circular polarization.

That result is completely inconsistent with the radiophysics determination of the field. It's a field that must occur in the atmosphere of the planet and is wildly inconsistent with the radio data, at least so far as they have been interpreted up until the present. Ten years ago, it was suggested by George Field** that there might be field strengths that strong in Jupiter's atmosphere, that is to say, field strengths of 10^4 gauss, and on the basis of the radiophysical data along, George Field concluded that the field didn't exist. The lifetimes of electrons, and particularly the spatial distribution of polarization of the synchrotron source, was inconsistent with that large a field.

* *Kemp, J.C., et al.*, 1971, *Nature* 231, 169, and 232, 165.
***Field*, G.B., 1960, *J. Geophys. Res.*, 65, 1661.

Kemp and associates suggest one other mechanism for the production of circular polarization, which is a reflection or scattering mechanism having to do with radiated transfer of the reflected sunlight through Jupiter's atmosphere, then back to the Earth. That seems to be a much more attractive hypothesis for this very weak polarized signal that they observed. A third possibility is that there is a spectral line in Jupiter's atmosphere which is Zeeman-sensitive. As yet, that line hasn't been observed spectrally, but it may be that Kemp and associates are observing the Zeeman pattern, so to speak, of a line which is strong in its locale of the spectrum but integrates out to a weak line in view of the entire spectrum. I don't know whether to believe that or not. It's wishful thinking, I suppose. But if it were hue, it would provide a direct path along which to measure the magnetic field of Jupiter.

As far as the shape and position of the field are concerned, I have made a strong case in CR-1685--at least, I hope it's a strong case. maybe it will be entirely shot down in the next two or three days. But I believe I've made a strong case for arguing that the field is essentially a dipolar field. I've also, over the last decade, argued that the field is decentral. This doesn't cut much ice so far as distinctions in synchrotron models are concerned. The field strengths in the radiation belts aren't determined by this decentralizing mechanism, so I think we can separate that out.

DR. MEAD: If the magnetic dipole is offset from the center of the planet, then the belts themselves would have to be offset by the same amount. There's no question about that.

DR. WARWICK: The belts themselves would have to be displaced in a north-south direction by the same amount, I believe.

DR. MEAD: And if there's any east-west or any radial displacement, then the belts would correspondingly be displaced.

DR. WARWICK: Right. But the east-west displacement is of the order of a tenth or two tenths of a radius at the maximum, so the exotic nature of that model is essentially in the north-south displacement, rather than the east-west one. Your question of whether that's confirmed or not, I think it's fair to say that it has not been confirmed. But the data that we have at hand are pencil-beam determinations by Ekers and Roberts*, which I discussed here, and a new set of data from Cal-Tech which Glenn Berge plans to discuss and an unpublished set of data from the Greenbank interferometer at 11 centimeters wavelength, none of which see the north-south displacement that I have quoted or ostensibly derived from the decametric data--or decimetric, too, so far as that is concerned.

I should emphasize, just in self-defense, that the centroid of the synchrotron emission is not the centroid of the magnetic field. For various reasons, where you observe the synchrotron source has to be carefully interpreted before it is equivalent to the centroid of the magnetic field. If that's a cop-out, read it as a cop-out. I have not yet in my limited wisdom been able to understand, if you will, the significance of the centered decimetric fields that seem to be what everyone finds who makes that measurement.

DR. LIEMOHN: I would like to point out one thing. The matter of the vertical displacement could be quite important, because the location of the field determines the relative position of the field with respect to the thermoplasma which is presumably distributed along the zenographic equator, and the wave propagation that you get through that medium strongly depends on the plasma and the field location and that the various wave modes in turn affect the location of the energetic electrons and protons. So it's a loop that would have to be closed.

DR. WARWICK: Incedentally, I feel with you that it's an important conclusion if the field is displaced. I didn't mean to put it down in that respect, but simply from the point of view of synchrotron interpretation, per se, it seems to me that that aspect of the model that I proposed is not particularly determining.

DR. BEARD: If the dipole is inclined to the ecliptic so that sometimes the dipole is pointed towards the Earth and sometimes away from the Earth, then if the radiation belts were a maximum in the magnetic equatorial plane, then you'd

* *Roberts, J.A., and Ekers, R.D., 1968, Icarus 8, 160.*

see an elliptical polarization, and might this be interpreted experimentally as giving you some small circular polarization, and the circular polarization in the synchrotron emission might result just from this--from the tilting of the dipole with respect to the ecliptic.

DR. WARWICK: I think that most people would agree that that should happen, and, in fact, there have been a series of observations of the radio source which suggests that that does happen, that there is a circular polarization at those times when the field is presented to us in this sense. And, again, in this sense, the circular polarization oscillates between those two extremes, and that it has a sense which is consistent with the decametric magnetic field sense which was gratifying to me. That is to say, there is a certain model dependence in interpretations of decametric emission, but that model of decametric emission, now about ten years old, turns out to have given the right sense of the field.

DR. BEARD: Would this explain the circular polarization you mentioned before?

DR. WARWICK: That was of optical radiation. That is a terribly difficult problem and a beautiful problem, if you will.

DR. HESS: Jim, you made the case in worrying about the radial diffusion of electrons that the Davis and Chang process seems to miss in time scale. That's been recognized since Leverett wrote the first paper on it, but I don't think that should cause particular concern in worrying about the Jovian electrons, because it's rather queer that that mechanism isn't the dominant radial diffusion mechanism of electrons in the Earth. So you can call them the same black magic, whatever it is, with the Earth and Jupiter and not worry about failure of that particular mechanism.

DR. WARWICK: I agree. I would add that we're talking about very energetic electrons for Jupiter, and I'm not so sure that the statement holds also for the relativistic electrons in the Earth's belt. Is it?

DR. MEAD: Don Williams has had some satellite data where he looks at one MeV electron in the, let's say, two to three Earth radii region, and they have seen, you might say, spikes of one end of the electrons appear not on the outside, but at a rather specific location in L and then gradually diffuse both ways, which has convinced him that there really seems to be mechanisms in the Earth which will produce energetic electrons at a particular point in radiation belts which cannot be explained from simple diffusion inwards.

DR. WARWICK: Right. Very nice.

DR. WHITE: In the diffusion that you're talking about now, are you saying that the mechanisms of Birmingham's electric field diffusion is too small in Jupiter?

DR. WARWICK: I'm not sure I understand the question. Some of you might.

DR. HESS: No, he's not. He's saying that he believes that the particles are radially diffused, and he's not arguing about the mechanisms.

DR. WHITE: I'm asking a further question. I'm saying if you take Birmingham's argument on the diffusion by electric fields and take the values that he comes up for for the Earth and then scale this for Jupiter in terms of magnetic field and put in the same kind of electric perturbations for Jupiter, are you saying that it's too small?

DR. WARWICK: I haven't done that. In fact, I don't know how to do that.

DR. BEARD: You said that Don Williams' one MeV data could not be explained by diffusion. Is it possible that there are energetic electrons of the order of 40 kilovolts, in the magnetosphere and that they diffused in, and produce MeV electron there? Moreover, is it possible that on the inside you might have a cutoff due to the atmospheric interaction of electrons in the Earth's field?

DR. MEAD: I'm not sure I understand.

DR. BEARD: Well, he said he observes one MeV, and then he observes electrons at, say, two Earth radii, and he doesn't observe one MeV electrons, as mentioned, within one Earth radii. Is it possible that that cutoff might just be atmospheric interaction?

DR. MEAD: The only point I was trying to make is these electrons rather suddenly appeared during the storm in ways in which you cannot explain the appearance by our normal concepts of what happens following adiabatic invariance, with violation of the third invariant or something like that during the storm.

DR. WARWICK: I have one point I'd like to make in that connection, which is that the energetic electron radiation belts of Jupiter don't appear to come and go quite so abruptly as Gil is suggesting, which isn't to say they might not, if we could look at the sufficiently detailed time and space scale, but one does have the intuition that the source is a rather more stable one. In fact, I use that argument to justify the kind of interpolation that I went through.

DR. MEAD: Is it not true, in fact, that the decimetric emission over a 12-year period has been really quite constant over that period?

DR. WARWICK: There's details on that. Some people think that is has been. Some people think that it's varied. In any case, the variations are small, and they're not dramatic on a day-to-day scale. That's clear.

DR. HESS: I think Don Williams' data does not argue against radial diffusion. It just says that there are mechanisms present besides Leverett Davis' mechanism. If you look at the general run-in of electron data, you find a monotonic increase with energy as you go inward in the outer belt, which you don't find on the L-cubed dependence. There's evidence for this general kind of process. There's also evidence for diffusion when you look at individual events, but it doesn't agree with the boundary-motion diffusion process.

DR. BEARD: You said it doesn't go as L-cubed. What does it go as?

DR. HESS: The average electron energy in the outer belt goes down sort of like one over L, doesn't it?

DR. WARWICK: It's a lower power than the third.

DR. VAN ALLEN: Is there any credible evidence for a short term pulse in the decimetric radiation?

DR. WARWICK: None.

DR. BEARD: What is the time resolution?

DR. BERGE: That is one of the problems. There haven't been many studies made of time scales more than a week or so. You can tell if there's a day-to-day variation.

DR. BEARD: But not a microsecond to microsecond?

DR. BERGE: Not microsecond to microsecond.

DR. SCARF: Isn't it true that there is a millisecond variation?

DR. BEARD: In the decametric data, yes.

DR. WARWICK: This is the microwaves we're talking about. The only report that I think should be given current reliability in this respect is by Gerard*, who used the Nancay big dish to study eleven-centimeter wavelength microwave variations which he correlates with solar activity successfully, he feels.

It's for anyone to look at the correlograms and make his own mind up. I find them a little bit less convincing than he has found, but the current state of the art in this type of correlation is certainly provided by Gerard in France, and it's published. You can make your own conclusions. Interpreting as a positive correlation, I would assume that Gerard has shown that

* *Gerard, E., 1970, Radio Science 5, 513.*

the electron lifetimes are a few weeks or a few months. They're not inconsistent with that.

MR. BECK: How does equal trapping fractions for the electrons and protons for Jupiter compare with what happens for the Earth and the same question for diffusion rates?

DR. WARWICK: As I said, there's no magic in it. It's clear what I did--what I assumed--but it's completely unclear how to do it correctly, and I certainly haven't got the wisdom that others in this room do. As I understand it, Mead talks about 1 in 10^6 protons from the solar wind trapped at the magnetopause and providing the proton belts. Do you still believe that, Gil?

DR. MEAD: I have not gone over those numbers for some time. I can't say any more about that.

MR. BECK: Do you find that the trapping fractions are the same for protons and electrons?

DR. MEAD: No. I don't believe there was any attempt to compare trapping fractions in the Nakada-Mead paper. We didn't even look at electrons. So I really can't say anything about trapping probabilities.

DR. HESS: The theory really doesn't work for electrons, so you can't answer that.

DR. BEARD: I have a student now working on entrance of particles into the magnetosphere, and from the work that we're doing, I would think that protons, because they have more energy in the magnetosheath would enter much more rapidly than the electrons would.

DR. WARWICK: That's bad news, of course, if it's true.

DR. WHITE: There's a lot of evidence on this. First of all, one can look at whether the sort of equilibrium fluxes in the outer radiation belt, and low-energy protons are higher in number than the electrons in order of magnitude. They about saturate the magnetic field. The electrons are lower, but the electrons vary much more with time than the low-energy protons do, and one can see them come in and go out and change with time.

As far as the trapping fractions are concerned, it is a very difficult thing to get until one knows the losses as well as the source, and one doesn't know these very well, so it's a very difficult thing. As far as I know, nobody has ever come up with a trapping fraction for either the protons or electrons.

DR. BEARD: Would you also say that the loss mechanism on Jupiter is apt to be quite different simply because Jupiter's atmosphere probably extends very much less than the Earth's atmosphere?

In terms of planetary radii, there's almost a one-tenth factor. The temperature may be lower and the gravitational pull is higher, and so roughly you'd expect the atmospheric scale height in terms of planetary diameter to be maybe one one-hundredth of what it is on the Earth.

DR. WHITE: I agree, and I've tried to get some good atmospheres and good ionospheres for Jupiter and have had difficulty finding those. I agree with you entirely. It would appear that at great distances from Jupiter that unless the lifetimes are extremely long--much, much longer than the case of the outer radiation belt of the Earth. I'm talking about thousands or tens of thousands or hundreds of thousands or maybe even millions of years--that the atmosphere can play hardly no role for the free electrons and the same for the ionosphere. Unless the lifetimes are extremely long, it can't play a role.

DR. WARWICK: Neil Brice* has actually proposed models for Jupiter's magnetosphere which involve the diffusion now in a different sense--the atmospheric-outwards diffusion of the energetic electrons produced from the excess photon energy from the solar ultraviolet flux, and so when these particles shoot into the magnetosphere, they produce a high temperature component, which in Brice's model combines the rotational aspects of the magnetosphere, and fills the

* *Ioannidis, G., ad Brice, N., 1971, Icarus 14, 360.*

magnetosphere with a relatively low density but extended plasma. I think that that plays an important role in his understanding of the Jupiter magnetosphere. I believe very strongly that there is an upper limit of density which one can play with so far as filling the Jupiter magnetosphere is concerned. People sometimes use the thermoplasma density almost as a free parameter to give them virtues that they haven't been able to find elsewhere in their theory. I object to that. I do believe that there are hard arguments, and we could equivocate on what those arguments are, perhaps, but there are hard arguments against such free parametrization of the thermoplasma. You were saying something which I substantially support. All the reasons why the thermoplasma of the Earth extends to, say, 4 or 5 Earth's radii are reasons why Jupiter's thermoplasma may be much more compact. Neil Brice is saying, "But those aren't the only factors in the equation." I buy that argument as well, but don't put in a hundred, no.

DR. NEUBAUER: I have another question about the thermal plasma in the Jovian atmosphere. Dr. Warwick said that there are indications, of course, that the proper plasma density is very low, and I was wondering whether it was something else in addition to the Faraday information you published earlier.

DR. WARWICK: No, that's the total of it.

DR. NEUBAUER: Then I wanted to ask other people how safe are the computations that determine Faraday rotation from plasma density. This could be important because it enters very strongly into the present particle stability considerations.

DR. GULKIS: I think the question boils down to whether or not there are one or two modes of propagation present. Dr. Warwick argues that two modes must be present, and I find no compelling reason myself for there being two modes present, although it certainly is a very likely probability. It depends, I think, where the interaction region is and how steep the gradients of the interaction are.

DR. WARWICK: I don't know how many of you are cognizant of the details of this, but the point is that the Jupiter decametric or low-frequency radio waves are elliptically polarized in many cases. That's well known. If you look at these waves in the correct way (and I think this is also widely agreed upon) you will find that they show a Faraday effect, which is the result of the Earth's ionosphere and magnetic field, per se. That is to say, the direction of the major axis of the polarization ellipse rotates both in time and in frequency at a rate which is determined by the Earth's ionosphere, not Jupiter's. The reason for this is that the elliptically polarized radiation from Jupiter which impinges on the Earth's ionosphere is split into left and right circularly polarized modes which propagate individually through the ionosphere but maintain their phase coherence, one with respect to the other. This means that as they are combined at the receiving antenna, the direction of the major axis of the ellipse is changed by an amount depending on the path difference which is measured by magnetic field strength and electron content multiplied by the path length. Now, the point is that this Faraday effect is quite typical for the Earth. We haven't discovered it. It's been known for many years, both from space physics, from radio astronomy, and so on. It depends on the fact that the incident wave splits into two circularly polarized modes. Whether these are appropriate to the wave is solely a function of wave frequency, magnetic field strength, and direction of wave propagation in the first instance.

Now, the point of my estimate of the magnetosphere of Jupiter is this, that if you backtrack from the Earth along the wave which is coming to you from Jupiter (going back in space along a given ray, which is now elliptically polarized) as it goes through the Earth's ionosphere, this wave finds itself in a medium receptive to circularly polarized modes and hostile to anything else. The wave wants to break down into circularly polarized modes. This is defined for us by the field strength and the direction of propagation. The same thing is true in interplanetary space, because the field strength there is very low. The plasma density is low, as well. Now, we go into Jupiter's magnetosphere, and the same thing is true as we begin to penetrate it. As we go through Jupiter's magnetosphere, the same conclusion continues to hold. The wave modes are the circularly polarized modes. It will hold up until such a point in space in the vicinity of Jupiter where the wave modes are no longer circular. Now, that will happen for Jupiter, first of all, in that location where the wave frequency and the electron gyrofrequency are comparable, say within a factor of ten. As you come down toward the surface of Jupiter, if the models that we've been talking about are anything like right, finally the wave will find itself in a region where elliptical polarization is the name of the game. At that point the Faraday argument changes its character qualitatively. But from that point to the Earth, the measurement of Faraday rotation is, in effect, a measurement of the electron content.

So from wherever the source of this radiation is (if, by source, we define the region where the wave frequency equals the electron gyrofrequency) the measurement of the Faraday rotation determines the electron content. I am not saying that I know where that source is, but I am making a vary hard statement that from that point on we do measure the rotation. Now, I might arm-wave and say that point is certainly within a Jupiter radius or so of Jupiter's surface. If that arm-waving argument is right, then this upper limit to the Faraday rotation sets an upper limit to the plasma density in Jupiter's magnetosphere, and that's the basis for the data that's in there.

CALCULATED LIMITS FOR PARTICLE FLUXES IN JUPITER'S VAN ALLEN BELTS

James Haffner[1]

The paper[2], and the results (which I will summarize here) were originally published about two years ago. Contrasted to many of you, my approach has been more of an engineering--"Let's get some numbers we can design spacecraft to"--rather than "Let's really try to understand the diffusion and source or loss mechanisms of the particles in the belts." I'd like to explain a little bit of the logic back of what I've done before I launch into the development of particle flux limits.

I do think that the logic here is correct, and in carrying it out, I have had to make two or three assumptions. The first assumption is that the particles in the Jupiter belts are really influenced by the magnetic field of the planet, and they're going to act the same as corresponding particles in the Earth's belts. If you have 10 gauss field somewhere, you're going to get a limiting flux and a given energy spectrum for both electrons and protons, regardless of whether you're at Jupiter, Earth, or any other planet with essentially a dipolar field, which is the second assumption. The particles, of course, are concerned with the magnetic field; not with the surfaces of the planets.

The third assumption is to use the Earth's belts as a model and, as best we can, scale from these belts, using as a limit the decimetric rf noise emitted from the planet. Here, the stability factor helps us a little bit along with the characteristics of the synchrotron radiation. As you all know, the more electrons you have, the weaker the magnetic field required to give a given total synchrotron power; or the stronger the field, the fewer electrons you need. There is a point at which you have a minimum field. Namely, the field is so weak that it has to hold all the electrons it possibly can to account for the observed synchrotron emission. The first part of my

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[1] *North American Rockwell Corporation, Downey, California 90241*

[2] *Haffner, J. W.; "Calculated Dose Rates in Jupiter's Van Allen Belts;"* AIAA J.; *Vol. 7; No. 12; pp. 2305-2311; 1969*

effort was to try to calculate this field and then, based upon spatially invariant particle densities, to come out with fluxes and, more importantly, dose rates, which a spacecraft must contend with.

Based upon Vette's tabulations of Van Allen belt electron fluxes, I calculated an effective characteristic energy, E_0, shown in Figure 1, as a function of distance from the center of the Earth along the equator based upon the parameter L. This is assuming an exponential function of the energy. These points were obtained by, frankly, just fitting exponential curves to the data, and, unfortunately, even on log-log paper I couldn't get quite a straight line. The data indicated by the open boxes in Figure 1 are probably going to be more significant for my work than the circles; the argument I came up with being that the characteristics of the Van Allen belts do change somewhat as you approach synchronous orbit.

With that kind of argument and by weighting the open box data heavily, I fit the characteristic energy with the following expression:

$$E_0 = 3L^{-1.36}$$

I assumed the L^{-4} spatial dependence calculated by Kennel and Petschek. I didn't consider any day-night asymmetry. I said, I'm going to see if I can fit the Vette data by something which has an L to the minus 4 spatial dependence and exponential energy dependence and put in the Earth's magnetic field at the equator of approximately three-tenths to the gauss and leave only one parameter, N, the relative population density. Since, of course, I'm just reasoning inversely to the stability calculations, sure enough, you get fairly good fits. Figure 2 shows the equation fitting the data. The solid lines are the electron data (electrons/cm^2-sec) in the Earth's equatorial plane as a function of distance from the center of the Earth. The dotted lines are the calculations, which for small L values and L values exceeding about 5, fit the data very well. The fits for the intermediate L values are not very good. The argument is adequate since we are interested in characteristics around the synchronous orbit, leaving one with N equaling one tenth. The shape here is determined primarily by the L^{-4} dependence.

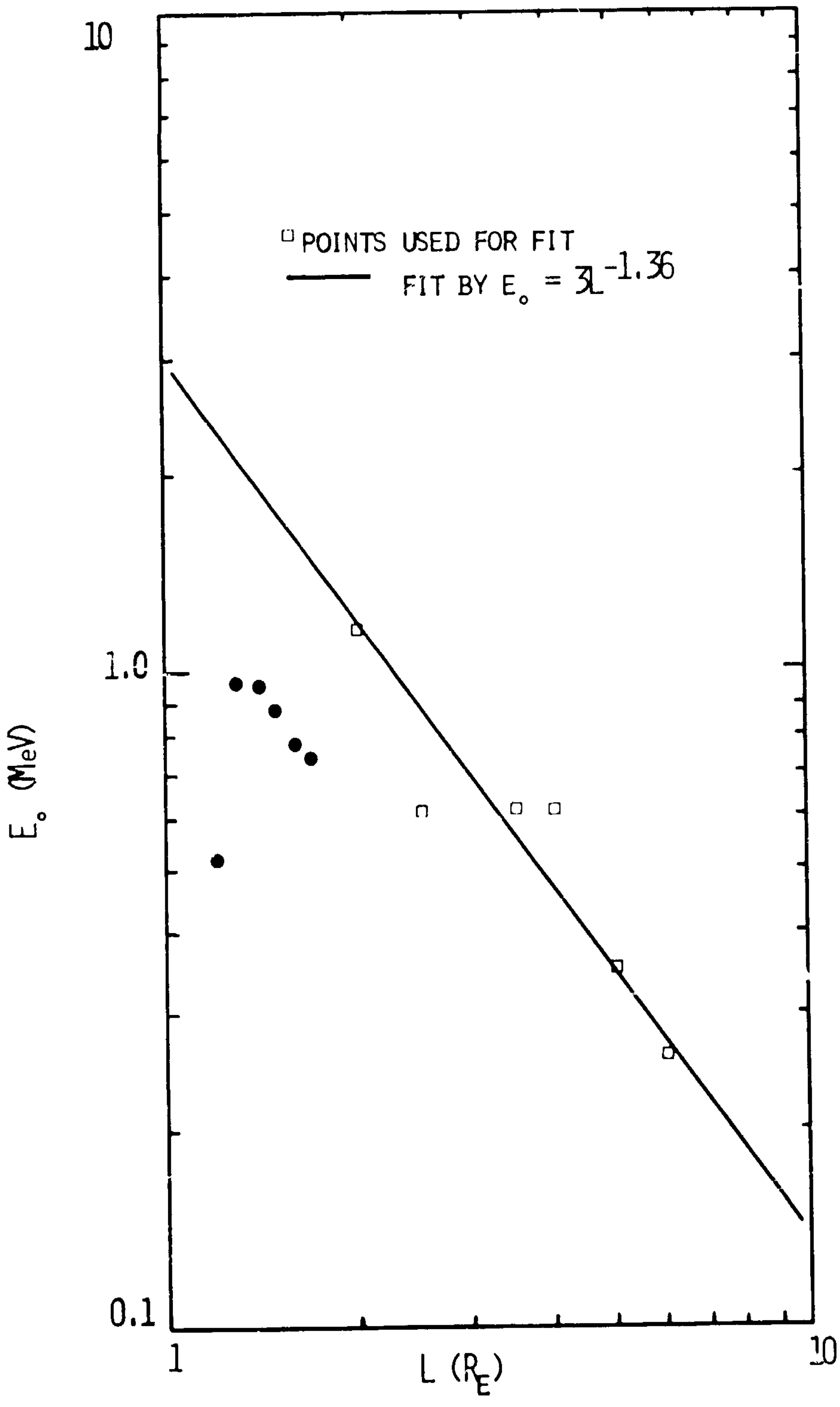

Figure 1. Radial Dependence of E_0 in the Earth's Van Allen Belt, Based upon an e^{-E}/E_0 Energy Spectrum

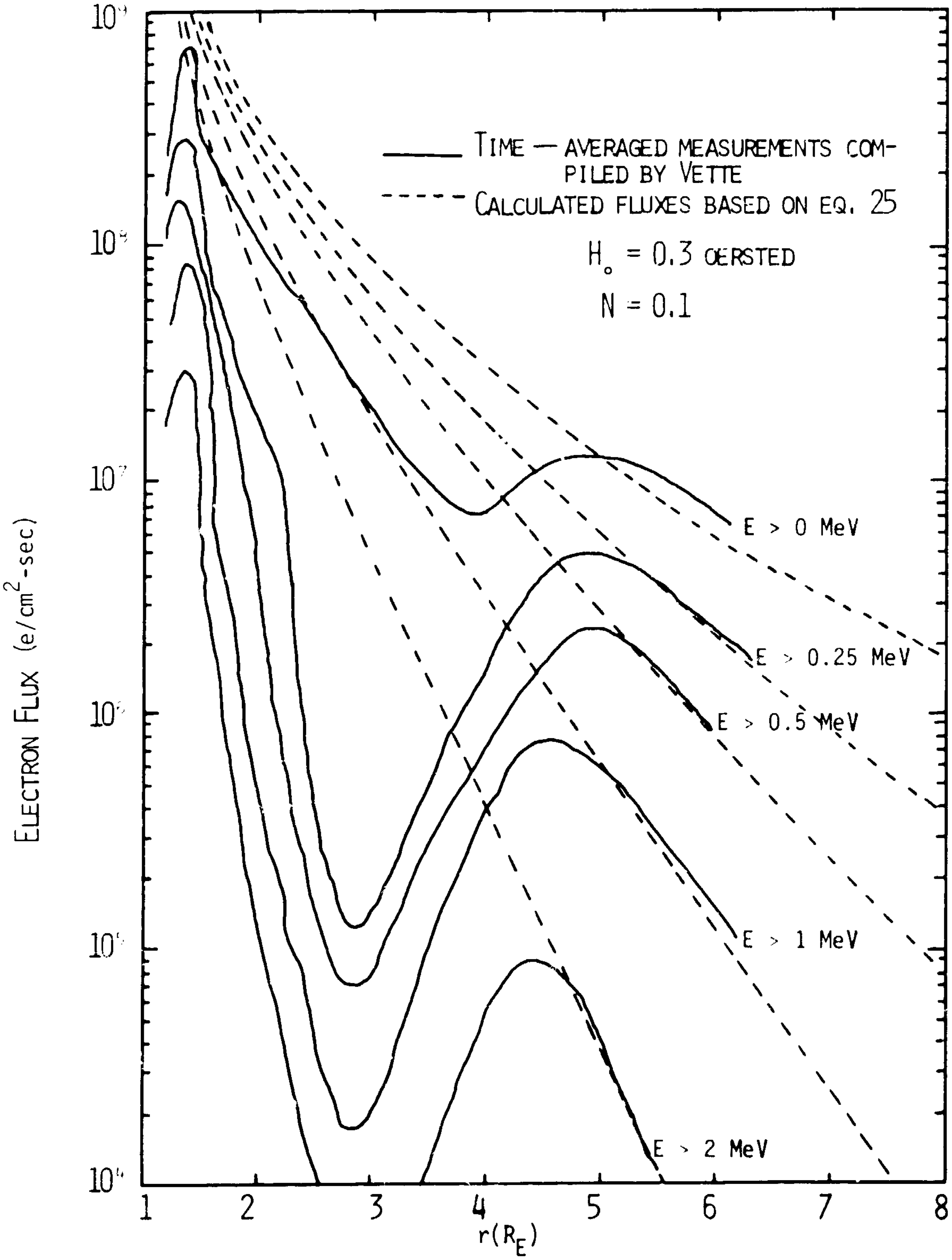

Figure 2. Electron Fluxes in the Earth's Van Allen Belt at the Geomagnetic Equator

If you look at the proton curves shown in Figure 3, the exponential factor is of greater importance since, of course, the characteristic energy is decreasing as you go out rather rapidly.

My previous papers (see footnote 2 herein) shows a very steep spatial dependence for the characteristic energy of the protons with distance from the center of Earth. The calculated numbers are represented by the dotted lines and the solid lines represent the measured values.

Now, how can I doctor up my function for the Earth's belts so that they fit for Jupiter? Based on the assumption that the magnetic field is the only significant characteristic, I come up with a four-thirds power dependence for the magnetic field since the dipole field obviously falls off as inverse cubed, and the flux falls off as inversed fourth, I want to make them approach the observed limit for the Earth's belt. In that case, I can come up with a function for the electron and proton fluxes in the equatorial planes of the planet Jupiter (based on the following parameters): H_0, the magnetic field at the visible surface of the planet, a, the effective inner radius of the belts, and, N, the relative particle density compared to the plasma stability limit.

Now, in order to get H_0, I have to go back to the argument that the stronger the field the fewer the electrons; the weaker the field, the more electrons. Figure 4 shows the decimetric radio noise emitted on the planet Jupiter. Essentially, what we did was say, okay, I've got a nonthermal component with 4.1 AU for the planet Jupiter. Then I assumed that this is nonthermal radiation isotropically emitted from the planet, which involved errors of factors of two or three, but to more precisely worry about it, it involved details which for the purposes of my calculation, I felt were well past the point of diminishing returns. For wavelengths from 2.5 cm on out, I integrated this and came out with something in the order of 3×10^9 W per m^2 (as radiated power from the planet Jupiter). This is what we must account for. Let's look at what a single electron is going to do in a given magnetic field.

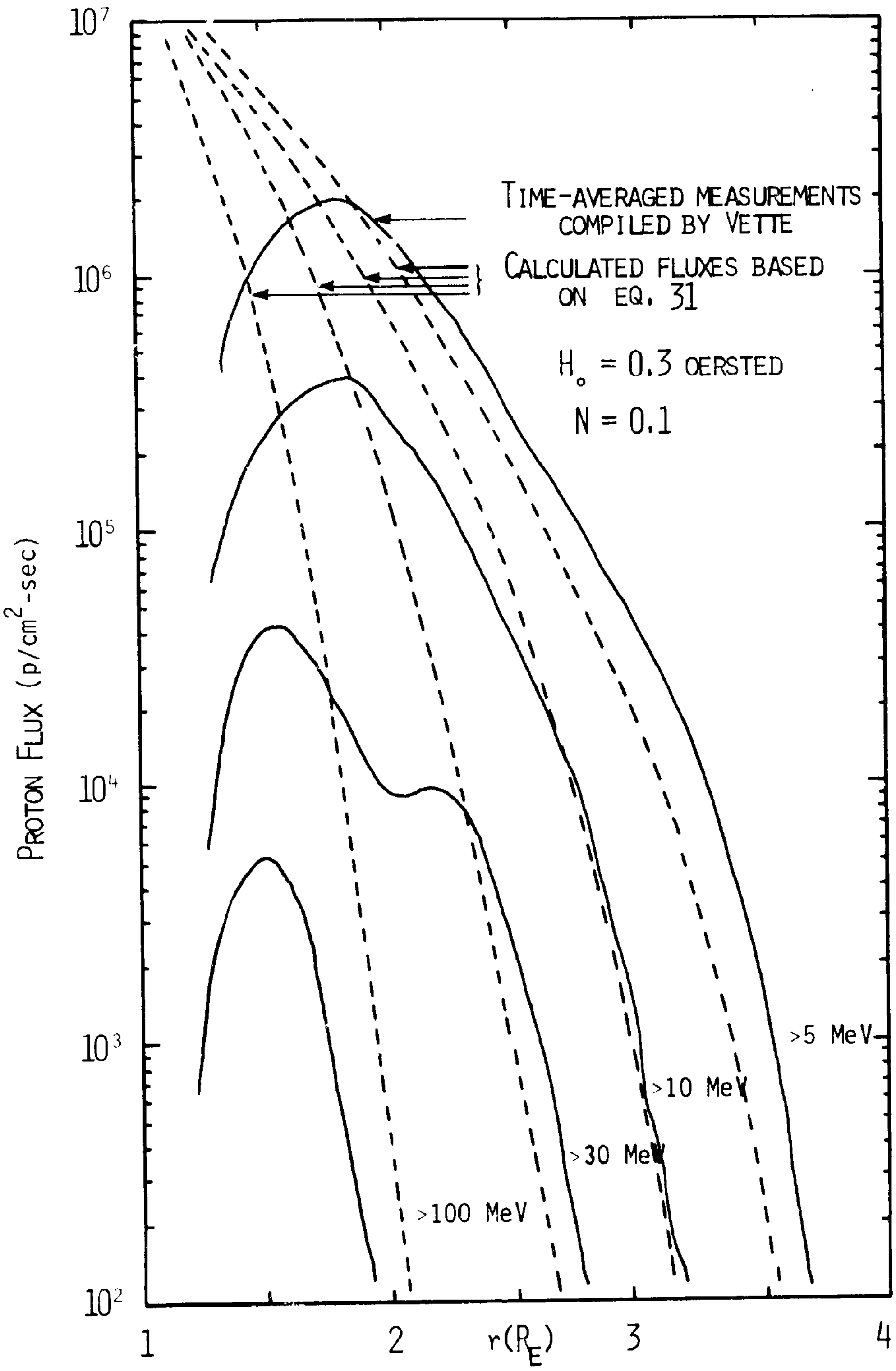

Figure 3. Proton Fluxes in the Earth's Van Allen Belt at the Geomagnetic Equator

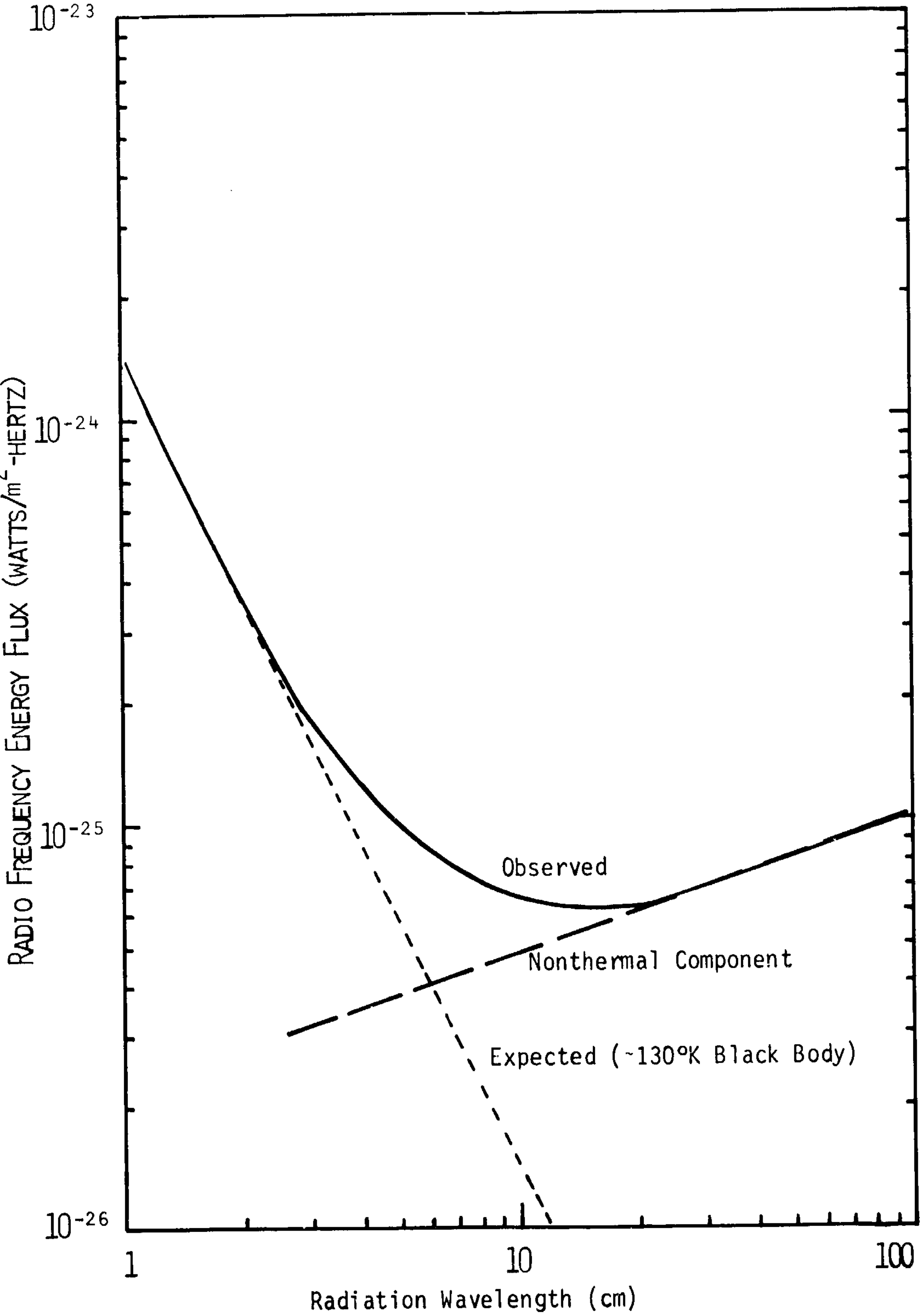

Figure 4. rf Decimetric Noise Received from Jupiter at Inferior Conjunction (Earth-Jupiter Separation = 4.1 AU)

Figure 5 shows the energy radiated by an electron multiplied by 10^{29}. This is the power radiated as a function of the frequency in terms of the characteristic frequency. The dots are points I took off of a graph based upon the classical expression. I wanted to come up with an equation I could integrate[1]. This equation fits quite well. You integrate this, and you come up with the power which one electron radiates, which, of course, is a function of the magnetic field the electron is in and, of course, the energy of the electron. Based upon the Earth's belts, I've got an expression for the energy spectrum of the electrons as a function of the magnetic field; so, really, I am down to the one parameter of the magnetic field.

The spatial integration I did perhaps leaves a little to be desired, also. I picked a constant angle as seen from the center of the planet of Jupiter of one radian, which gives a fan-shaped spatial distribution in one plane, used the theorem of Pappus to integrate around the toroid, and then equated that, which of course, is a function of the magnetic field and a parameter a (which is an effective inner radius of the Van Allen belts) to the the calculated power radiated, assuming, again, the planet radiates isotropically. When you solve this for the magnetic field parameter as a function of a, effective inner radius of the belts, and N, the population related to the plasma stability limit, you wind up with the curves shown in Figure 6. This figure shows the log-log plots of H_0, the equatorial magnetic field of the planet (in oersted) in terms of a, the effective inner radius of the belt in Jupiter radii and N, population density relative to the plasma limit. N is obviously less than 1, and a is obviously greater than 1. Because of the rather steep dependence on the value of a, these curves are fairly steep. They are not as far apart as you'd expect, based upon the value of the parameter N. To me, the surprising thing of this calculation, which admittedly involves some factors of 2 and perhaps 3 approximations, is the fact that one comes out with a field as low as something on the order of one-half of a gauss, especially in view of the fact that the numbers usually used are likely to be 10 or 15 gauss.

The assumptions, incidently, involved in this calculation, for the most part tend to be conservative with one exception. I have mentioned the assumption that the planet radiates. according to this model, isotropically.

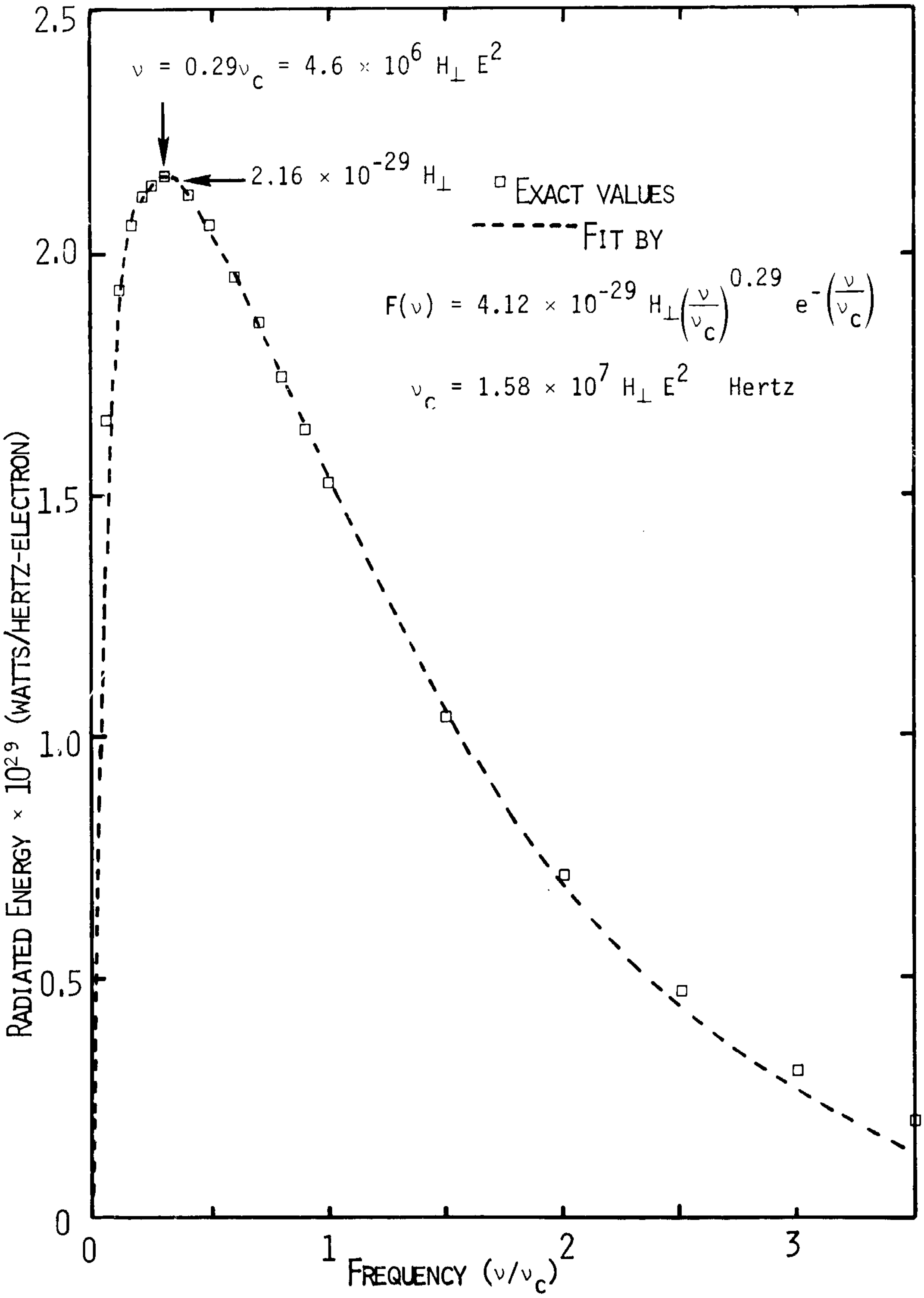

Figure 5. Spectrum of Synchrotron Radiation Emitted by a Single Relativistic Electron in Uniform Magnetic Field

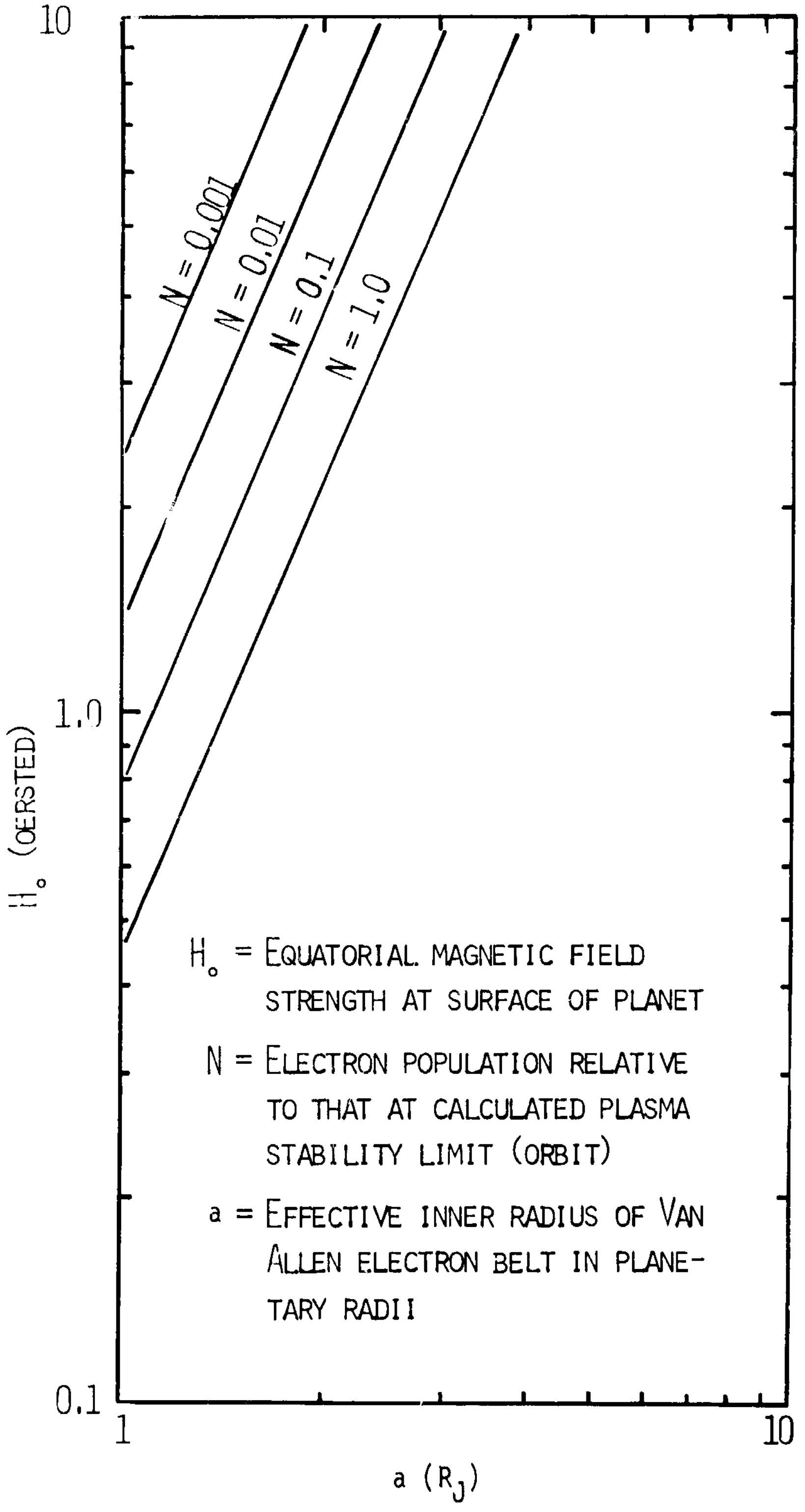

Figure 6. Calculated Relationship Between H_0, N, and a for Jupiter's Van Allen Electron Belt

If it radiates primarily in the equatorial plane, I'm being conservative. If it radiates primarily at the poles, which I don't believe is probable, it's non-conservative. The opacity of the planet plays a very small role here. Even if the planet were totally transparent, you're talking about an error of from 10-15%, even for small values of a.

The synchrotron frequency being higher than the plasma frequency for the densities involved, the self-attenuation of the rf by the Van Allen belts turned out to be a very small factor. If it turns out, on the other hand, that there is a hefty amount of thermal plasma which attenuates this rf, then by that factor, this model could not be conservative.

So far, all we've got is a relationship of (at best) an approximate nature between H_0, a, and N. How can we go from this to the fluxes and doses of the Van Allen belts on Jupiter? Well, remember the formula we came up with for Earth's belts had H_0 as a parameter. We had E_0 for the electrons as a function of L, which, of course, I turned into a function of H_0. Then I chose three sets of parameters of a, H_0, and N for further investigation, i.e., values of 2, 5, and 15 oersted, of 1.2, 1.4, and 1.8 Jupiter radii, and for N, 10^{-2}, 10^{-3} and 10^{-4}, respectively.

I can't really defend that choice of those parameters as contrasted to others, except that if the solar wind, as generally believed, is the source of the belts out there, the solar wind behaves adiabatically beyond 1 AU. Thus, you might expect that the average population density of the Jupiter belts would be somewhat less than that of Earth, especially in view of the fact that you've got the Galilean satellites tearing good-sized holes in them. As it turns out for the values concerned, the dose rates you get are about the same. In particular, if you have a weak magnetic field, you're going to have a lot of electrons, but they're not going to be terribly energetic, at least by Jupiter's standards. Therefore, the dose rates will be not as high as you would expect on the basis of the number of electrons alone. If you have a strong magnetic field, the number of electrons you need will be relatively low, but they're going to be pretty energetic.

Figure 7 shows the ranges of the electron point dose rates. This, incidentally, is for tissue. The difference between tissue and silicon dose rates for electrons is not great, fortunately. The graphs show doses in rads per hour in the equatorial plane of Jupiter by these models, as a function of distance from the planet. The thing which is interesting is that even though we've got almost an order of magnitude in the magnetic field uncertainty, two orders of magnitude uncertainty in the population density, and a nonnegligible uncertain effective inner radius, the total dose rates you get come out about the same--plus or minus about a factor of 3.

This band of dose rates shows what I calculated for a tenth of a gram per centimeter shielding. I used aluminum, but for electrons, it doesn't make a lot of difference, until you get to the place in the shielding of electrons where bremsstrahlung takes over. The other dose rates are for one gram per square centimeter and ten grams per centimeter.

While these numbers are not exactly the kind of thing that makes spacecraft designers happy, when you get to about three Jupiter radii, which is a typical swing-by periapsis, you're talking in the order of 10^4 rads/hr. You're talking about a transit time of a few hours, so obviously you're going to have to use hardened electronics.

In the corresponding calculations for the protons, based, as I say, solely upon the modeling from the Earth's Van Allen belts, the proton dose rates shown in Figure 8 come out quite comparable. They have about the same range of values except that they do drop off somewhat more steeply because of the stronger dependence of the characteristic energy of the protons on the magnetic field strength. These, I should point out, are tissue dose rates. The difference between tissue and silicon for protons is appreciable, so that the silicon dose rates would be a fair amount lower.

Still, you can see at 3 Jupiter radii, we're talking something of perhaps 10^3 rads/hr--numbers which, as I say, don't make anybody happy, but at least people who deal with radiation hardness and radiation effects on electronics tell me that they can live with it.

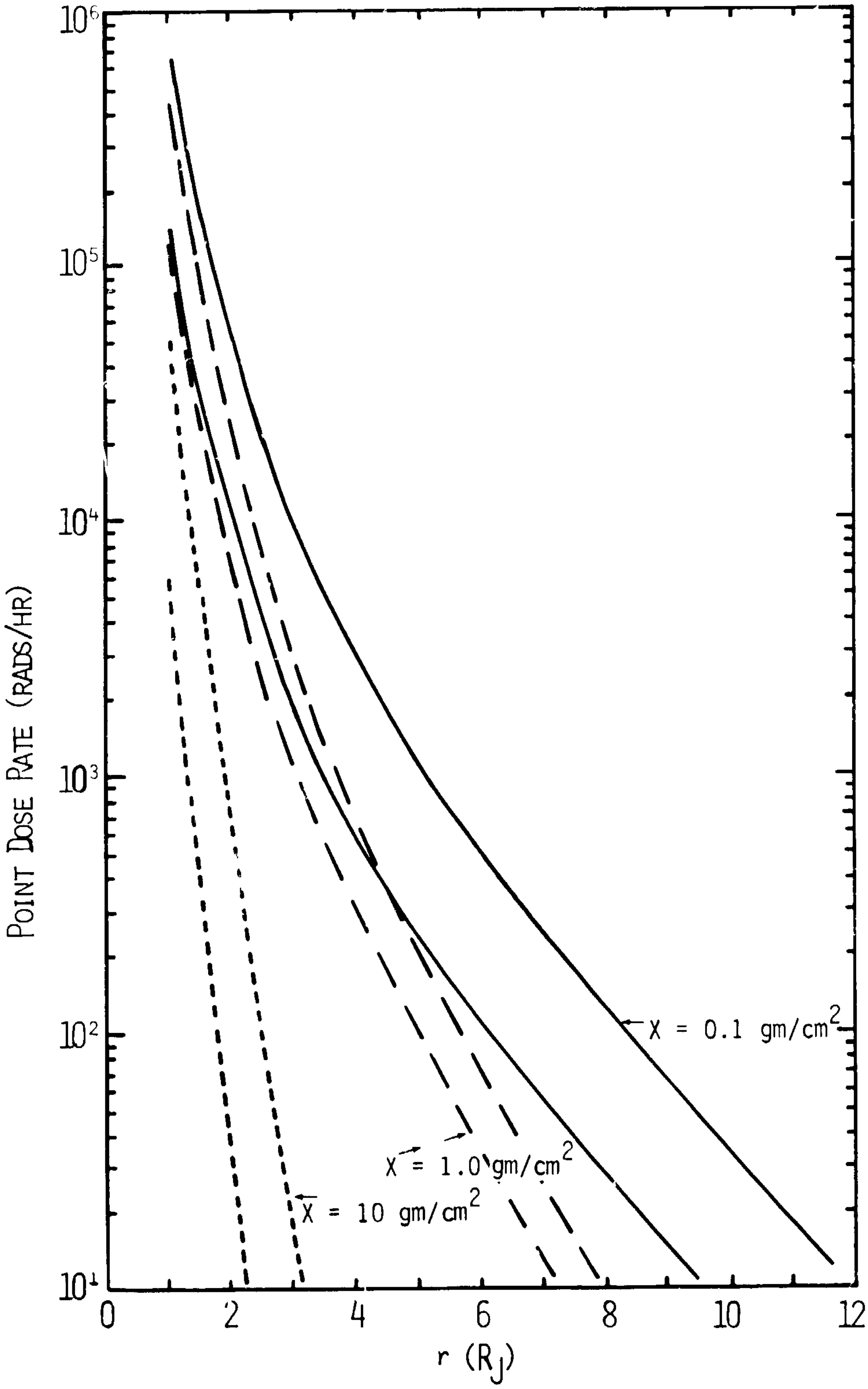

Figure 7. Envelope of the Calculated Electron Dose Rates in the Plan of Jupiter Magnetic Equator

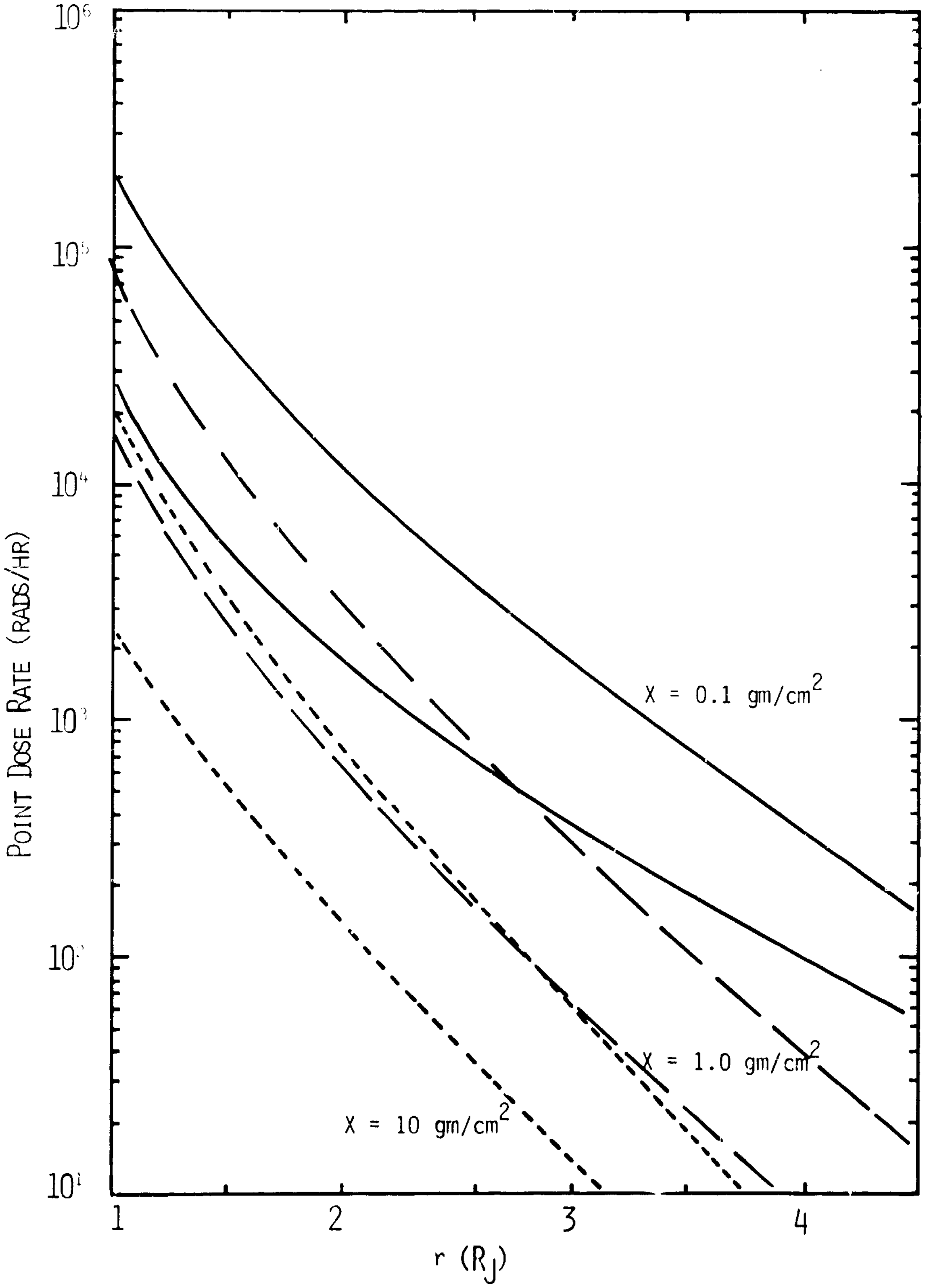

Figure 8. Envelope of the Calculated Proton Dose Rates in the Plane of Jupiter's Magnetic Equator

In conclusion, let me recapitulate briefly what I have done and point out again the assumptions which are involved. I've assumed that electron characteristics are determined only by the magnetic field they are in. Each electron is influenced by the magnetic field only and not by the other electrons or protons around; that the magnetic field of Jupiter is essentially a dipole; that the radiation of a decimetric nature received from Jupiter is synchrotron due to these electrons, and that to a first approximation it is emitted isotropically; and that the strength of the emission in the decimetric wavelength range gives us an upper bound, if you will, considering how strong the field can be and how many electrons you have.

Obviously, the stronger the field, the fewer energetic electrons you have, so that combinations of the magnetic field and the electron population turn out to yield dose rates which do not vary as much as the assumed uncertainties in the input parameters lead you to expect.

That, essentially, is the gist of what I have to say. I'd be happy to hear about any additional assumptions which I may have slipped in, as well as the particular point that has me worried--the possible attenuation of the synchrotron emission by thermal plasma or other aspects of the Van Allen belts around Jupiter.

DISCUSSION

DR. MEAD: At what point did you bring in the synchrotron equations? What was the relationship between synchrotron emission and the flux brought in to normalize the electrons?

DR. HAFFNER: I calculated the power radiated by one electron as a function of its energy in its magnetic field. Since we have electrons going in all directions with all sorts of energies and pitch angles, I assumed that the power is radiated isotropically. Then I said, okay, I have a magnetic dipole field. I have an assumed L^{-4} flux distribution, and, therefore, let's put this L^{-4} flux distribution in the dipole field with the variable parameters being: N (the population density, compared to the plasma stability limit) and H_0 (the magnetic field, at the surface of the planet). Then I integrated spatially over this toroid, which I approximated with a fan-shaped toroid. Here is an electron of a certain energy in a certain field radiating so much. Here is another electron of another energy in another field radiating so much; summing by integrating over energy and space, whichincludes electron density, you come up with a total radiated power as a function of these parameters. There's not much energy received at the Earth, so let's equate them and see what we can determine in relationship between N, H_0, and A, which are the three parameters left. The relationship between them is shown in Figure 4 (herein).

DR. MEAD: Did you say that the protons were normalized simply by saying that there is a certain ratio of flux of the protons to electrons on the Earth and that this ratio is the same ratio for Jupiter?

DR. HAFFNER: This ratio is a function of the magnetic field, the characteristic energy of the electrons and protons that I took as a function of the magnetic field in terms of the distance of the planet. I said, at a certain distance from the Earth, you have a certain magnetic field, you have a certain flux, and you have a certain characteristic energy. I'm going to assume that the characteristic energy, the shape of the spectrum, and everything is the same for Jupiter as it would be for Earth.

DR. GULKIS: Can you explain what the physics is behind the limiting flux?

DR. HAFFNER: Well, Dr. Kennel wrote the article on it. Perhaps he would address that point.

DR. KENNEL: Well, I'll say a little something about it on Thursday, but we're not sure that Jupiter is all that important. In any case, there is an instability of whistler- and ion-cyclotron mode waves which will go unstable when pitch-angle distribucion is anisotropic. When the stability goes to reasonable amplitude, it will scatter particles in pitch angles out of the Van Allen belts, and you can estimate in a very rough way what flux it takes in order to create this stability. You then argue that if you had a source of particles--radial diffusion or local acceleration--that as particles approach this marginal stability flux, they couldn't get too much above it because if they did, there would be a large instability. The particles would be scattered out in the belts.

DR. BEARD: What is the time, roughly, that you would estimate for this instability to take over?

DR. KENNEL: Well, you can make one estimate dependent on the wave amplitude; that is, go to the limit where you're well above marginal instability and assume that you have a very large wave amplitude. Then you assume this is indicating an isotropic didtribution of electrons and protons. When you have an isotropic distribution, then the lifetime just depends on the size of the loss cone, and it goes essentially L^4. In Jupiter, beyond about L=8, that's a very long time to reduce the fluxes back to the marginal stability. Close-in, of course, it's a very short time. In the Earth, the time scale for electrons at L=6 is the order of five minutes for electrons and the order of 2,000 seconds for protons.

DR. WHITE: Would this be effective in the outer radii of Jupiter?

DR. KENNEL: You could have all the instability you wanted in the outer region of L=8, and you could never get rid of the particles on a reasonable time scale.

DR. WHITE: But would you expect this to be effective close-in to Jupiter at the high energies that one would have if one assumed the adiabatic invariants?

DR. KENNEL: That is the question we will address ourselves to.

DR. DAVIS: I'm still not clear on one point. You say that you make the assumption that the properties, ratio, proton and electron fluxes, etc., depend on the field strengths, whether it's Jupiter or the Earth...Now, in the Earth, you don't get any field strengths greater than 3/10 of 1 gauss, and even when you get to 0.2 gauss, you're probably so low that you may have to worry about fluxes that you don't have to worry about in Jupiter. Do you assume that the Jupiter field strength is so small that this doesn't bother you?

DR. HAFFNER: I just plain extrapolate. In effect, I'm using the data from the Earth far enough away that the temperature is not going to be a factor; but, admittedly, this means that the fact that I have to extrapolate--at least another magnitude or more in a magnetic field--is the resultant. That's really what I had to do, because I don't have any first-hand experimental data of Van Allen belts in a 1-gauss field.

DR. KENNEL: I think it's all right to do that, at least if you're using arguments that fluxes will build-up to a stability limit, because that ended up being dependent only on the B field, anyway.

MR. THOMAS: Clearly, it seems to me that the spectrum really depends on a lot more than just the whole B field in the sense it's the gradient that determines how high energy can be trapped. Of course, all the loss mechanisms affect that also, particularly when Jupiter has a much larger distance scale for a variation of the main magnetic field. That is due to its larger radius. That could introduce a factor of 10 uncertainty in a characteristic energy.

DR. HAFFNER: Well, if it turned out that the average time which the particle was trapped was comparable to, or shorter than the time it diffused-in (or was being removed from the belts), I think you'd have an extremely good point. Then what I've done would be even more questionable, but I made the assumption, and at least for the parts of the radiation belt where the hardest radiation is emitted, I haven't seen anything to indicate that the 1) trapping time is quite long compared to the time for the particles to diffuse-in, acquiring whatever energy they have, and 2) trapping time is long compared to the time for them to be scattered out (or otherwise lost from the radiation belts). So, if you look at the holes as the satellites tear them, even allowing for the fact that the satellites go around fast, there's an awful lot of space between them. Therefore, I have convinced myself that that wasn't going to invalidate the assumption that the belts have an essential degree of long-term stability, which means I can reasonably make this assumption.

DR. CARR: Do you conclude that the dose rate doesn't vary very rapidly as does the magnetic field strength, and over what range of the magnetic field does this occur?

DR. HAFFNER: Well, I made range computations for 2 to 15 gauss, and N values of 10^{-2} to 10^{-4}. Having picked those two values, I have determined my a values: 1) an a value of 1.2, as being perhaps representative of the dipole; and 2) an a value of 1.8, as being an extreme model. Certainly there are other combinations you can pick. You can pick a field of a hundred gauss, for instance, and perhaps an N of 10^{-6} to 10^{-7}. I didn't explore this region--I took what I considered to be the most probable set of parameters. It's possible that if you pick values outside of this that these uncertainties could enlarge. I still think, in view of the fact that the more electrons, the weaker the field and visa versa, that these uncertainties aren't going to enlarge as rapidly as the ranges of the parameters you choose.

DR. LIEMOHN: Do you feel that if the choice of E_0 (the characteristic e-folding energy) were to change appreciably, that it would affect your results?

DR. HAFFNER: I think it would have to change a great deal, because E_0 is high, close to the planet where the bulk of the radiation takes place; and below E_0, the spectrum is rather flat. There's an exponential, you know. So, I would think that this would be a second-order effect, though I haven't quantitatively investigated this. All I can give you is an opinion.

DR. WHITE: Well, the E_0's that you have plotted appear to me to be E_0's which were characteristic of the Starfish injection of electrons. They came out with E_0 = 1 MeV, approximately. That is very high for the natural electrons in the Earth's radiation belt, which should be more like one-tenth of that. Do you remember at what time period those E_0's were selected by Vette?

DR. HAFFNER: I published a book a couple of years ago, and I used what was the most up-to-date data that I could get my hands on then. To the best of my knowledge, the Starfish belts have essentially decayed to relative unimportance in determining E_0 in time. At L=2, it was less than 1 MeV, if you remember correctly.

DR. WHITE: You have $3L^{-1.3}$, and at L=2, the curve was about 1 MeV. That would indicate to me that it was about 1.5 MeV on your graph at L=2. That seems too high for data that I'm familiar with from a natural belt. The E_0 at that point, I think should be about 0.1 MeV.

DR. HAFFNER: I see the point you're making now. Figure 1 has some data indicated by black dots for L < 2 and some data indicated by boxes for L > 2, and the boxes, if you draw a straight line through them, fell above the black dots. It wasn't until you got up to something like L=3 that the line fits the data well. It's coming up with a higher E_0 than the data indicated for L < 2. But beyond that, it was in reasonably good agreement. In Figure 2, I worried also about the points between L=2 and L=5 because of the fact that the electron flux drops way down in this region, indicating, of course, that either the source mechanism isn't doing its work or the loss mechanisms are getting out of hand. Since I assumed a spatial invariant, N, for population density, again, I waved my arms and said, I'll use values which I get from Earth for about three Earth radii. But your point is made. I made an approximation here, and I can't really say how far I can get away with it.

DR. WHITE: I have another comment. On the protons--and in doing the modeling to go from the Earth to Jupiter, using only the magnetic field--it appears to me that they are somewhat in question. When one tries to calculate protons in the Earth's radiation belt, one has sources and losses he considers;

and the magnetic field comes in only as upper limits on what one can put in, usually. The major considerations are not the magnetic field, at least where the high energy protons are relatively close to the Earth. So, I wonder if one isn't missing the major sources and losses and thus the major parameters that go into the radiation belt population if one just scales a magnetic field.

DR. HAFFNER: Well, in terms of the actual spatial distribution, it's quite possible that the spatial distribution is widely different than what I've assumed, but for every electron you take out from someplace, you've got to put in a corresponding electron or adjust some of the parameters so that the synchrotron emission from the electrons goes up. The cornerstone of my argument is that you have a magnetic field and some electrons; the combination of the two has to add up to what we took.

DR. WHITE: I'm talking about protons. I have no evidence on protons.

DR. HAFFNER: Now, on protons, again, it's quite possible you're right. The characteristics outside of the source and loss mechanisms are such that the proton distribution may be a fair amount different than what I assumed. I'd be surprised if it's radically different just becaust the electrons and protons like to stay around each other, and one goes more or less where the other one goes. If the lifetime of particles in the belts is not long compared to the source and loss mechanisms, then the two distributions could be quite different.

DR. HESS: I'll argue tomorrow that they are radically different, and that there are essentially no high-energy protons in the Jovian belt and the point you made about the equality of densities is handled by the thermal flux. You didn't have to worry about there being a lack of high-energy protons if you have high-energy electrons. That's no problem. Charge neutrality is not a problem. You have to argue sources and losses of the populations in order to make up your mind about what the proton flux is. I think the losses are very substantial. As a matter of fact, you won't find the kinds of dose rates in protons nor the kinds of fluxes that Jim Haffner suggested.

DR. HAFFNER: Let me come back and point out this--that even if you take the protons away completely, you're talking about factors of 2 or 3 in the dose rates. The people I work with say, "I don't give a darn how the particles get there. What I want to know is how hard I have got to make my electronics so they will survive." Whether the protons are there or not, I don't think anybody will argue about electrons being there, and unless you put more than 10 g/cm^2 (to shield the electronics), your electrons are going to be the particles that hurt you.

EQUATORIAL ELECTRON ENERGY AND NUMBER DENSITIES IN THE JOVIAN MAGNETOSPHERE*

Joe L. Luthey**

INTRODUCTION

The nonthermal component of decimeter radiation from Jupiter has been shown to be consistent with synchrotron emission from electrons trapped in a Jovian magnetosphere. For a recent review of the Jovian magnetosphere, see Carr and Gulkis (1969). Models for synchrotron radiation from a dipole magnetic field have been computed by Chang and Davis (1962), Thorne (1963, 1965), Ortwein, et al. (1966); Clarke (1970), and others. The dominant energy spectrum for these models has been power law of the form E^{-1}.

In this investigation, a synchrotron model with a Maxwellian energy distribution of the form

$$e^{-E/E_0}$$

has been used in a comparison with spatially resolved radio interferometric measurements of the Jovian emission. This has led to the equatorial radial dependence of the radiating electron number density, the average kinetic energy, E_0, and corresponding radiative half-life. In particular, the most recent results have considered the contribution of an isotropic distribution of electrons between pitch angle cutoffs. These results are compared with an early work, Luthey and Beard (1971), referred to as Report I, in which the extreme ansotropic distribution of pitch angles at 90° was used.

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** *University of Iowa, Iowa City, Iowa 52240; work performed in collaboration with David B. Beard, University of Kansas, Lawrence, Kansas 66044.*

RADIO DATA

Berge (1966) and Branson (1968) have taken radio interferometric measurements of the Jovian decimeter radiation at 10.4 and 21 cms wavelength, respectively. They have each compiles their observations into two-dimensional temperature contour maps, which describe the spatial distribution of the emitted flux across Jupiter and its radiation belt. Berge's contour plot is resolved both North-South and East-West across Jupiter. Branson's plots resolve only the East-West polarized component of the 21 cm radiation, and the best resolution of the flux is in the equatorial plane. The half-power beam widths are approximately 13" arc at 4.04 AU for the 10.4 cm data and 23" arc at 4.8 AU for the 21 cm data.

From these maps, the temperature was taken from the magnetic equatorial plane and converted to flux by means of the Rayleigh-Jeans Law. For each temperature map, the East and West limb equatorial measurements were averaged as a function of radial distance. This has the effect, for the 21 cm data especially, of smoothing and centering the data on the planet disc.

The data in the more recent work is taken from Branson's temperature map centered at 15° system III central meridian longitude (CML) to correspond with Berg's map at 20° system III CML. This differs slightly from the data employed in Report I, in which the 21 cm fluxes came from the temperature map and strip scan at 255°K ±40°K while the 10.4 cm temperature map is strictly the nonthermal emission. Figure 1 is a graph of nonthermal equatorial flux densities in cgs units of erg $sec^{-1}/cm^2/Hz$.

The data at both wavelengths extends nearly to 4.5 Jupiter radii (R_J). If one limb of the planet and radiation zone is divided into twenty intervals, $0.25R_J$ wide out to $5R_J$; and if the equatorial plane is divided into concentric annuli of identical width, then the partitioning of the radiation zone is as shown in Figure 2. The V_{ij} refer to the area of the i^{th} interval intersected with the j^{th} annulus times a thickness of 1 cm of the equatorial plane.

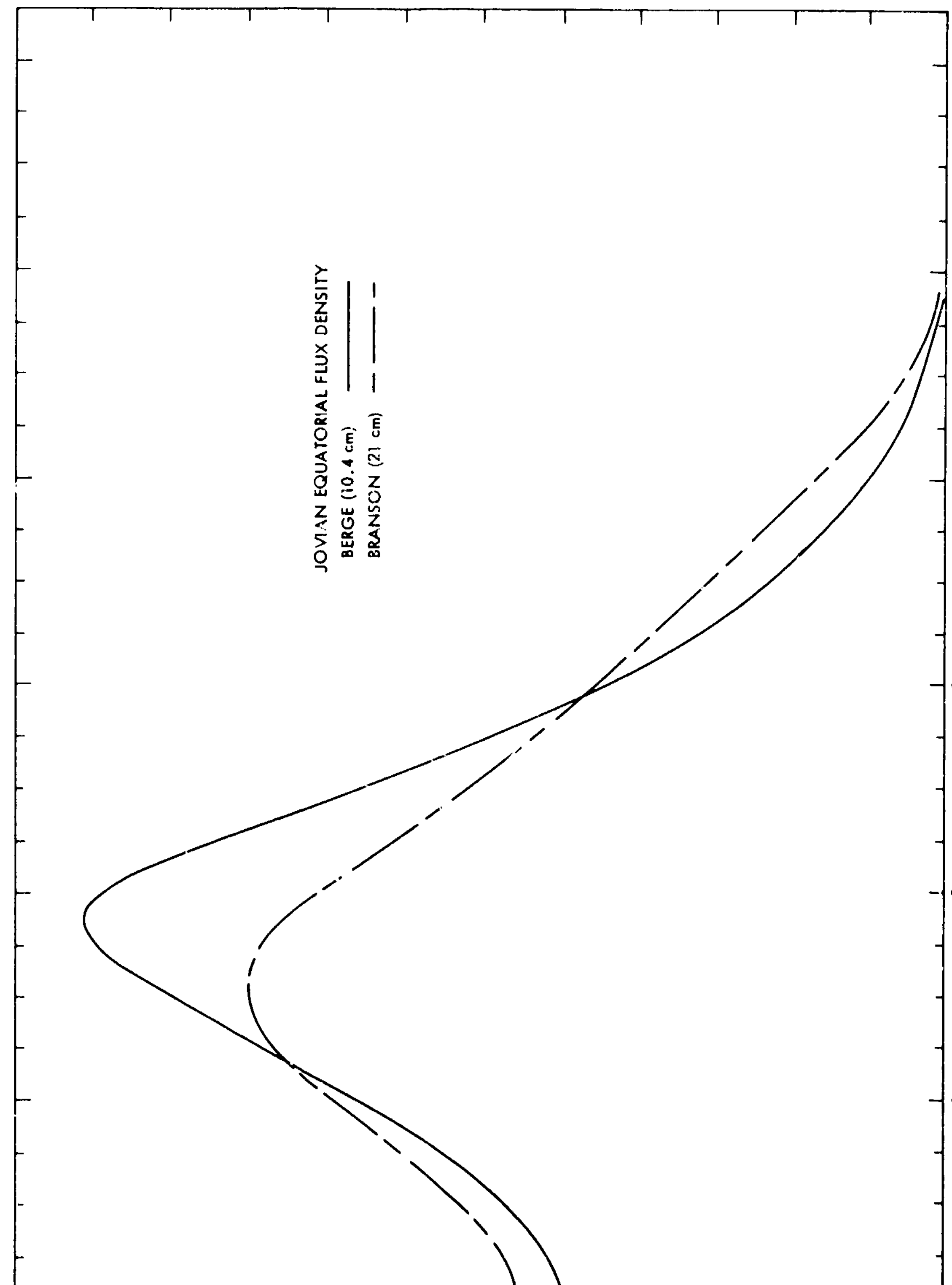

Figure 1. Flux densities in ergs sec^{-1}/cm^2/Hz from the magnetic equatorial plane of the temperature maps

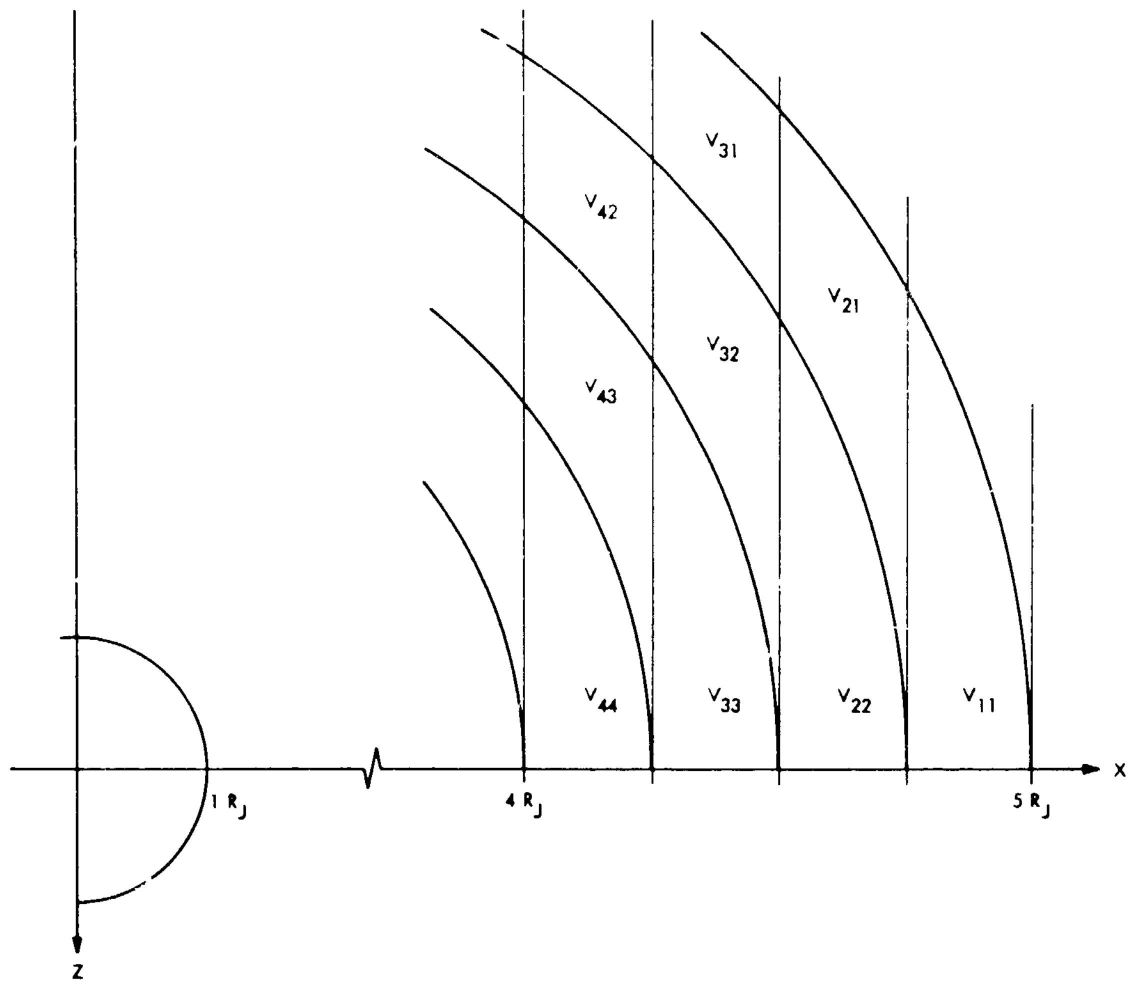

Figure 2. Polar view of partitioned equatorial plane. The V's in the text refer to volumes of identical elements in quadrants I and IV

The flux from the outermost interval is

$$S_1 = n_1 \frac{\Delta P_1}{R^2} V_{11} \tag{1}$$

where n_1V_{11} is the number of electrons in volume V_{11} emitting total power $\Delta P_1(\nu,r)$ in the region between 4.75 and $5R_J$. The distance, R, between the observer and Jupiter is 4.04 AU. The flux from the next outermost interval is

$$S_2 = n_1 \frac{\Delta P_1}{R^2} V_{21} + n_2 \frac{\Delta P_2}{R^2} V_{22} \tag{2}$$

and so on up to S_{16}.

We define

$$D_1 = n_1 \, \Delta P_1 = \frac{S_1 R^2}{V_{11}} \tag{3}$$

$$D_2 = n_2 \, \Delta P_2 = \frac{R^2}{V_{22}} \left(S_2 - \frac{V_{21}}{V_{11}} S_1 \right)$$

.

.

.

etc.

for each annulus in the equatorial plane. The D's are apparently the emitted power per cubic centimeter of source and relate all the unknowns, n_i and those contained within ΔP_i, to the observational data. Given the D's at two different wavelengths, at least the number density can be eliminated as an unknown by simple division. A graph of the D's vs R at the two wavelengths and their ratio is shown in Figure 3.

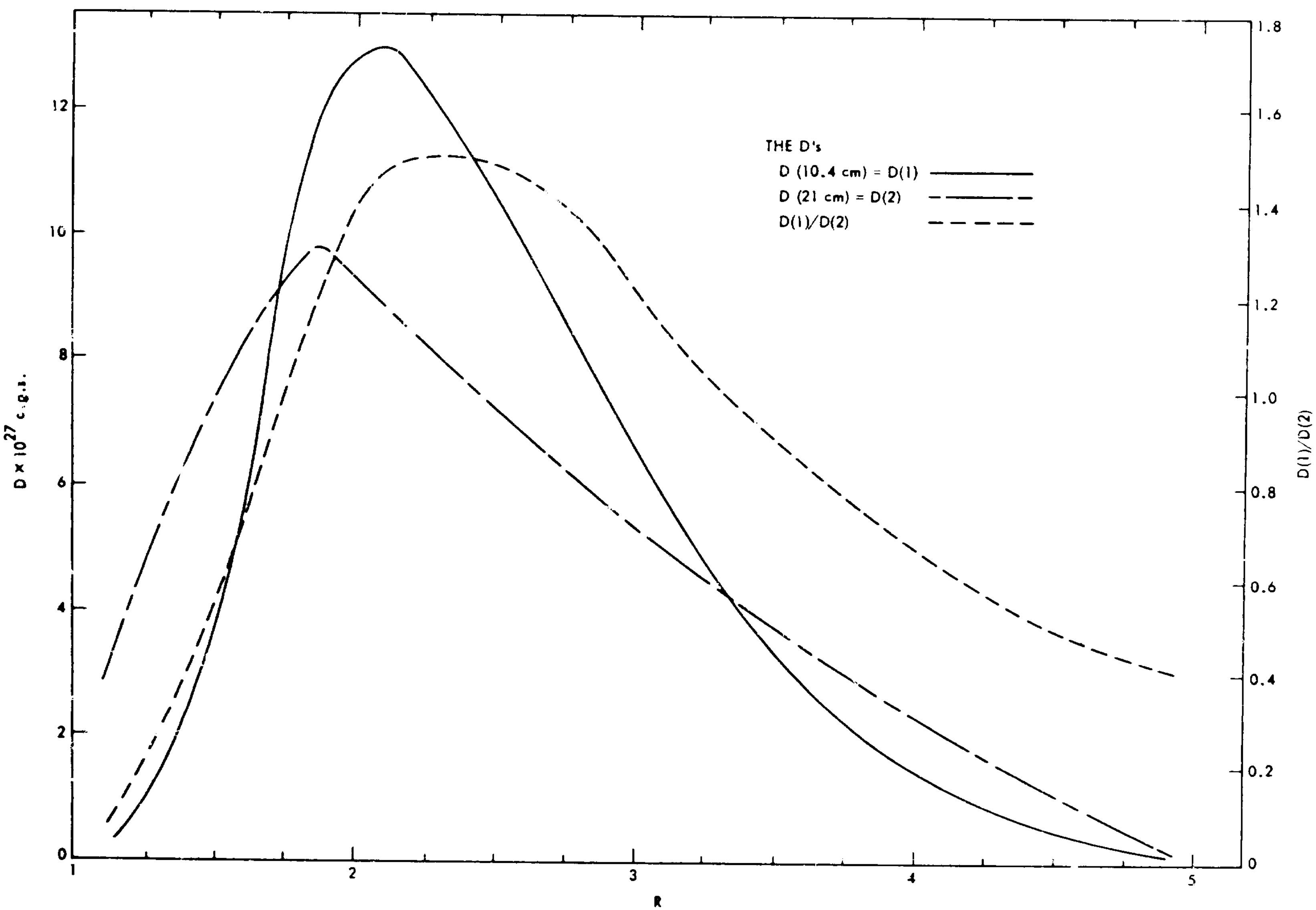

Figure 3. The radiated power per cm^3 in the equatorial plane vs equatorial distance and their ratio

THE EQUATIONS OF POWER

The emission from a relativistic electron spiraling along a magnetic field line has been developed by Westfold (1959) and Epstein and Feldman (1967). The total power emitted per Hertz for an electron with pitch angle α is

$$P(\nu,\alpha) = \frac{\sqrt{3}\, e^3 B}{mc^2 \sin\alpha} F\left(\frac{\nu}{\nu_c}\right) \quad (4)$$

where

$$\nu_c = \frac{3}{4\pi}\frac{eB}{mc}\left(\frac{E}{mc^2}\right)^2 \sin\alpha \quad (5)$$

is the critical frequency for an electron of total energy E in a magnetic field B; and

$$F(x) = x\int_x^\infty K_{5/3}(\eta)\, d\eta \quad (6)$$

The power per Hertz of the radiation polarized perpendicular to the magnetic field direction is

$$P^{(2)}(\nu,\alpha) = \frac{\sqrt{3}\, e^3 B}{mc^2 \sin\alpha} F^{(2)}\left(\nu/\nu_c\right) \quad (7)$$

where

$$F^{(2)}(x) = \tfrac{1}{2}x\left[\int_x^\infty K_{5/3}(\eta)\, d\eta + K_{2/3}(x)\right] \quad (8)$$

In Equations (4) and (7) it is assumed that $E/mc^2 \gg 1$ and that $\alpha \gg mc^2/E$.

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The power at 10.4 cm wavelength is computed using Equation (4), since Berge's data is resolved in directions parallel and perpendicular to the magnetic field. Equation (7) is appropriate for computing the power at 21 cm wavelength, since Branson's data is resolved only for East-West polarization. Thus, the 21 cm equatorial intensities will be entirely perpendicular to the magnetic field lines of the dipole to be assumed later.

The emission from a small volume of relativistic electrons in the direction of an observer is obtained by summing the incoherent contributions over pitch angle. The distribution in velocities is taken to be isotropic with the form

$$\rho(\alpha) = \frac{\sin \alpha}{2 \cos \alpha_L} \tag{9}$$

between pitch angle cutoffs, α_L. Due to the beaming of the emission cone, the radiation received is assumed to be negligible for those electrons whose motion is not within an angle α^* measured between the magnetic field line and the observer. Then upon integration over pitch angle, the power/steradian/Hz is approximately

$$\frac{dP(\nu, E, \alpha^*)}{d\Omega} = \frac{1}{4\pi \cos \alpha_L} P(\nu, E, \alpha) \tag{10}$$

where α^* is the angle of observation.

The electron energy distribution function is taken to be a Maxwellian of the form

$$n(E) = E_0^{-1} e^{-E/E_0}, \tag{11}$$

where E is the total electron energy, but E_0 is average kinetic energy. The integration over energy and volume containing n number of radiating electrons per unit volume yields the power emitted at radius r from the planet center in planetary radii.

$$n(r)\ V_{ij}\ \Delta P(\nu,r,\alpha^*) = \frac{n(r)}{4\pi\ \cos\ \alpha_L}\ \frac{e^{mc^2/E_0}}{E_0} \int_0^\infty e^{-E/E_0}\ P(\nu,E,\alpha^*,r)\ dE \int_V dV \quad (12)$$

and a similar expression involving Equation (7) for power polarized perpendicular to the field line. The direction of observation is taken to be $\alpha^* = \pi/2$ in the equatorial plane. Over the width of an annulus, the number density and the radiated power are assumed to be constant so that the volume integral is constant, viz., V_{ij}.

The dependence of the power on radial distance comes in through $E_0(r)$ and B(r) the magnetic field intensity. The magnetosphere below $5R_J$ is assumed to be an undistorted dipole with an equatorial surface field intensity of B_0. The magnetic field in the equatorial plane is then

$$B(r) = \frac{B_0}{r^3} \quad (13)$$

THE POWER EQUATIONS FOR THE EXTREME CASE, $\alpha_L = \pi/2$

The results of an earlier work (Report I) are applicable to the case of extreme anisotropy, a delta function in pitch angle (P.A.) distribution of $\alpha = \pi/2$. With the angle of observation at 90° to the magnetic field line, the emitted power/steradian/Hz is entirely polarized perpendicular to the field line, and the power/steradian/Hz from Schwinger (1949) is

$$\frac{dP}{d\Omega}(\nu,E,r) = \frac{e^2\nu}{\pi_c}\frac{mc^2}{E}\frac{\nu}{\nu_c}K^2_{2/3}\left(\frac{\nu}{2\nu_c}\right) \tag{14}$$

where ν_c is defined in Equation (5) with $\alpha = \pi/2$. With the same assumptions as in the previous section on volume, magnetic field intensity and number density, the integrated power/Hz over the same Maxwellian energy distribution is

$$n(r)\,V_{ij}\,\Delta P(\nu,r) = n(r)\int_0^\infty e^{-E/E_0(r)}\frac{dP}{d\Omega}(\nu,E,r)\frac{dE}{E_0(r)}\int_V dV \tag{15}$$

In later sections the results of Report I will be compared to those of the more recent work on the emission from an isotropic distribution of electrons between pitch angle cutoffs.

THE RATIO OF THE D'S

The ratio of the D's at one wavelength to the D's of the other wavelength is equivalent to computing the ratio

$$\frac{D(\nu_1)}{D(\nu_2)} = \frac{n(r)\ \Delta P(\nu_1,r)}{n(r)\ \Delta P(\nu_2,r)}$$

$$= \frac{\int_0^\infty e^{-E/E_0(r)}\ P(\nu_1,E,r)\ dE/E_0(r)}{\int_0^\infty e^{-E/E_0(r)}\ P^{(2)}(\nu_2,E,r)\ dE/E_0(r)} = \frac{f}{g} \qquad (16)$$

The assumption here is that the number density is the same at both wavelengths. Note that the ratio does not depend on the pitch angle cutoff.

For the isotropic P.A. distribution, we define the variable

$$a_1 = \sqrt{\frac{3\nu_1 mc}{4\pi\ eB(r)}\frac{mc^2}{E_0}} \qquad (17)$$

in which the subscript 1 refers to a wavelength of 10.4 cm. For a wavelength of 21 cm, a subscript 2 defines a similar variable related by

$$a_2 = \sqrt{\frac{\nu_2}{\nu_1}}\, a_1 \qquad (18)$$

Substitution of Equations (17) and (18) into Equations (4), (7) and (16) gives a ratio of $f(a_1)/g(a_2)$ vs a_1, as shown in Figures 4a and 4b, which decreases monotonically with a_1 from a peak of 1.6 with a_1 near zero. For a given ratio of $D(\nu_1)/D(\nu_2)$, the corresponding value of a_1 yields the energy $E_0(r)$ by substitution into Equation (7). Clearly for plausible values of E_0, the ratio of the D's must be somewhat less than 1.6.

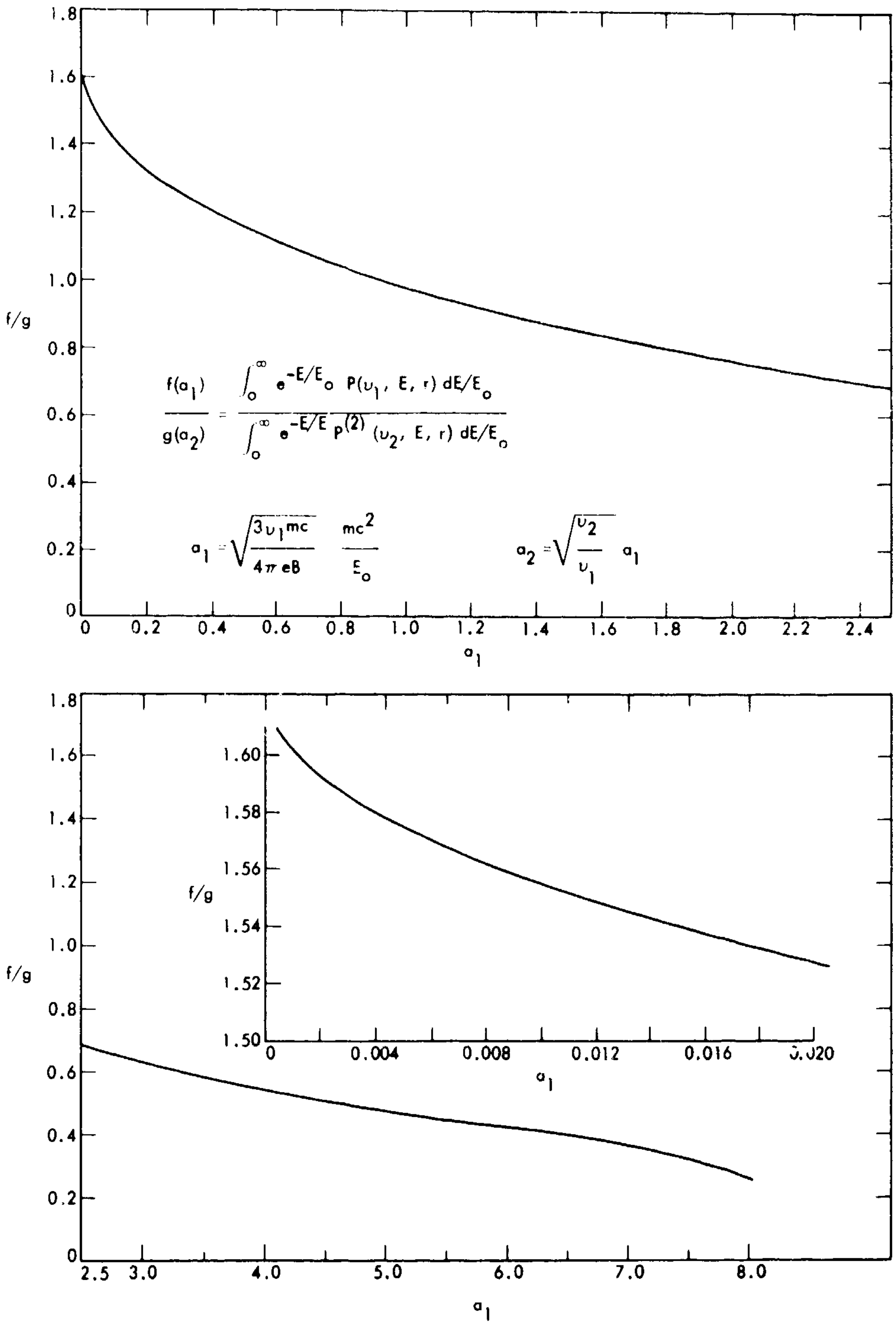

Figure 4. Ratio of the integrated power over a Maxwell-Boltzmann electron energy distribution with isotropic distribution of pitch angles. f is the combined power of both directions of polarization and g is the power emitted perpendicular to the magnetic field lines

For the extreme anisotropic P.A. distribution where $\alpha_L = \pi/2$, the integrals in Equations (15) and (16) were evaluated by several approximations. The details may be found in Report I. There the relevant parameter $E_0(r)$ was found by an iteration process until the ratio of the integrated power/Hz at the two wavelengths was within a small neighborhood of the ratio of the D's.

NUMBER DENSITY AND RADIATIVE HALF-LIFE

The number of radiating electrons per unit volume can be found from the definition of the D's in Equation (3). The power is computed from E_0 and a corresponding B_0. With E_0 determined, the maximum allowable number of electrons, n', is obtained from the pressure balance equation

$$n'(r) = \frac{3B^2}{8\pi} \frac{(2 + \sin^2 \alpha_L)^{-1}}{E_0} \tag{19}$$

The radiative half-life is computed only for those electrons of equatorial pitch angle of 90° and average energy E_0.

The radiative half-life is computed only for those electrons of equatorial pitch angle of 90° and average energy E_0. The power radiated from an electron in a flat orbit is given, e.g., by Schwinger (1949),

$$P(t) = \frac{-dE}{dt} = \frac{2}{3} \frac{e^2}{m^2c^3} \left(\frac{E}{mc^2}\right)^2 \left(\frac{d\vec{p}}{dt}\right)^2 \tag{20}$$

where $d\vec{p}/dt$ is time rate of change of the momentum, $(E/mc^2)m\dot{\vec{v}}$. An integration over time and total energy from average kinetic energy E_0 to 1/2 E_0 gives the radiative half-life

$$\tau_{1/2} = \frac{3}{4} \frac{m^3c^5}{e^4B^2} \ln \left(\frac{E_0 + 3mc^2}{E_0 + mc^2}\right) \tag{21}$$

DISCUSSION AND RESULTS

A. *Average Electron Energy*

For the data in Figure 1, a Maxwellian energy distribution and an isotropic P.A. distribution, the computed average energy is shown in Figure 5. The peak energy occurred between $2.25R_J$ and $2.5R_J$, including several surface equatorial magnetic field intensities, B_0, not shown in Figure 5. This peak corresponds identically with the maximum in the ratio of the D's in Figure 3. From $3R_J$ to the limit of the data at $4.5R_J$, the radial dependence of the average energy is r^{-3} for B_0 = 7 gauss to 25 gauss. Below $2R_J$, the energy falls off as r^8 for decreasing r.

Figure 6 is a comparison curve of the average energy for the delta function P.A. distribution, $\alpha = \pi/2$ with B_0 = 7 gauss. For either P.A. distribution, an increase in equatorial magnetic field from B_0 = 7 to 25 gauss resulted mainly in decreasing the peak average energy by factors of 2 to 3.

The peak value of 70 MeV for the delta function P.A. distribution is considerably lower than 460 MeV in the isotropic case for B_0 = 7 gauss. This large variation, though slightly confused by using 21 cm flux densities at two different longitudes, must be attributed mainly to the differences in pitch angle distribution. To the limit of the accuracy of the data and the validity of the Maxwell-Boltzmann energy distribution, the actual energies should lie between the two extreme cases, since the P.A. distribution is anisotropic as indicated by Roberts and Komesaroff (1965), Thorne (1965), and others.

The position of the peak energy in the delta function case lies between 3 and $3.5R_J$. This difference in peak position using an isotropic P.A. distribution is almost certainly the result of using 21 cm data at 255° system III CML instead of 15° CML. Emission at 21 cm wavelength and 15° CML exceeds that of 10.4 cm and 20° CML from $3.25R_J$ to the radial limit of the data. However, over the same region the 10.4 cm emission exceeds that of 21 cm wavelength at 255° system III CML. In the first instance, the ratio of the D's,

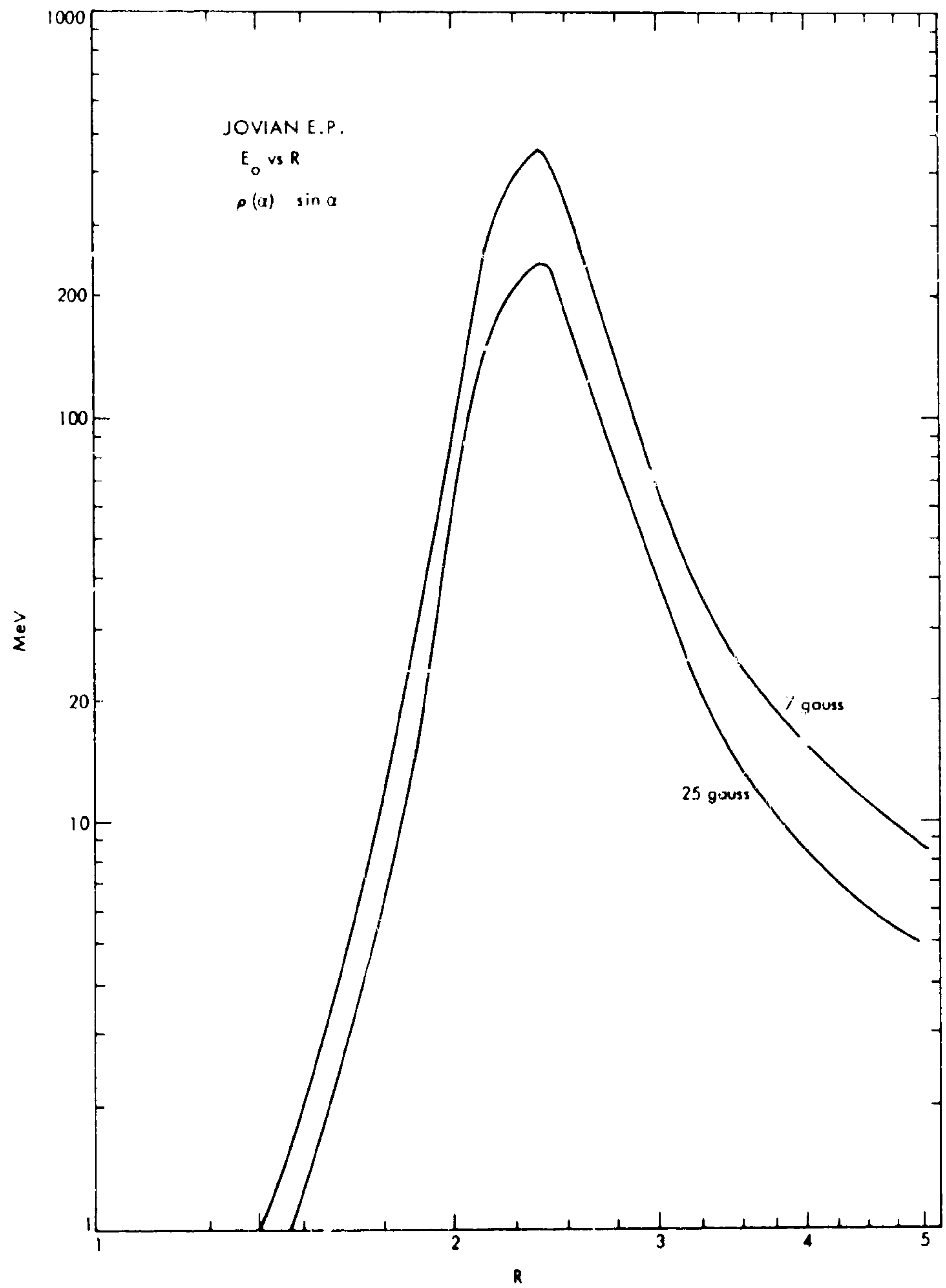

Figure 5. Average energy in the equatorial plane for an isotropic P. A. distribution between pitch angle cutoffs

as taken in Equation (16), is less than one and greater than one in the other case. Although E_0 depends on $B(r)$ and especially the ratio of the D's in a complicated way, the position of maximum E_0 is primarily a function of the ratio of the D's. Preliminary results indicate the peak in E_0 is at $2.5R_J$ using 21 cm data from 15° CML and a delta function P. A. distribution.

For the energies derived in Report I, the radial dependence below 2.5 radii was r^6 and approximately r^{-3} beyond $3.5R_J$.

If an acceleration mechanism conserving the first adiabatic invariant is assumed to supply the energies implied above, the two straight, parallel lines in Figure 6 give the energy below $4R_J$ for electrons injected at the subsolar point with initial energies of 5 keV and 25 keV. By comparison with the earth's magnetosphere, the Jovian subsolar point is at $49R_J$ for B_0 = 7 gauss. These energies obtained by diffusion ignore radiation loss or other losses on the nearly infinite diffusion time for a relativistic electron in the Jovian magnetosphere (Brice and Ioannidis, 1970).

B. *Number Density*

For the isotropic pitch angle case, the electron number densities in the equatorial plane were computed in the form $n/\cos \alpha_L$. For a typical pitch angle cutoff, say $\alpha_L = 45°$ as indicated by the Chang and Davis (1962) thin shell model, the number densities in Figure 7 would be reduced by 0.7. The secondary peak at $2.5R_J$ coincides with the position of maximum average energy. If the helices flatten with increasing energy as suggested by Komesaroff, et al. (1970), the secondary maxima would be lower by an undetermined amount due to the dependence on $\cos \alpha_L$.

For the P.A. distribution of electrons in flat orbits, the equatorial number densities were independent of the B_0's and their corresponding E_0's. In Figure 8, we see that the density decreases with increasing radial distance, whereas it increases with distance in the isotropic case. Also, the number densities for flat helices start almost an order of magnitude below those in the ositropic case at one Jupiter radius and fall two more

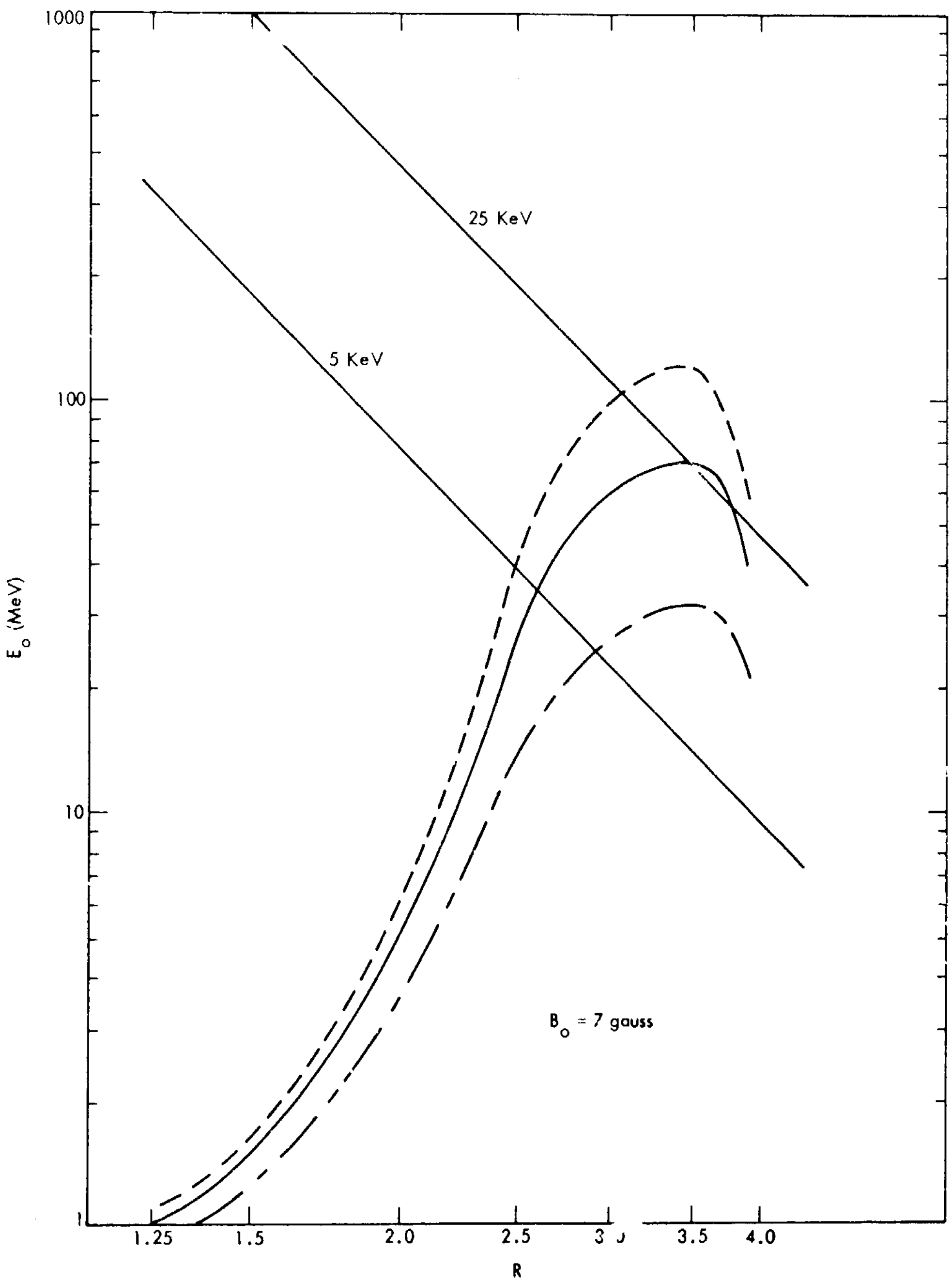

Figure 6. Average energy in the equatorial plane for electrons in flat orbits using 21 cm data from equatorial strip scans at 255° system III CML. Also shown are cases of Berge's data raised uniformly 10% relative to Branson's (--------) and Branson's intensities raised 19% uniformly to Berge's (— — — —). The straight lines are the resulting E_o's for injection at 49 R_J and the indicated energies, assuming a conserved first invariant

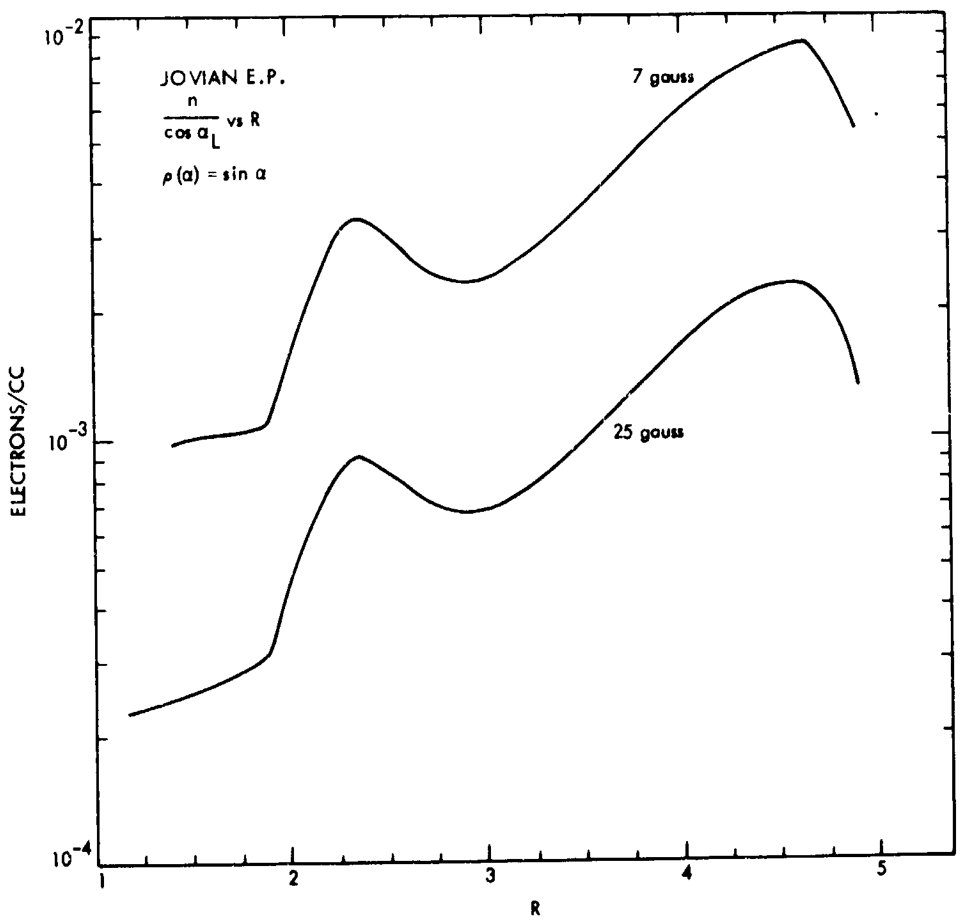

Figure 7. Equatorial number densities of isotropic P. A. distribution for E_0's corresponding to the indicated equatorial surface magnetic field intensities

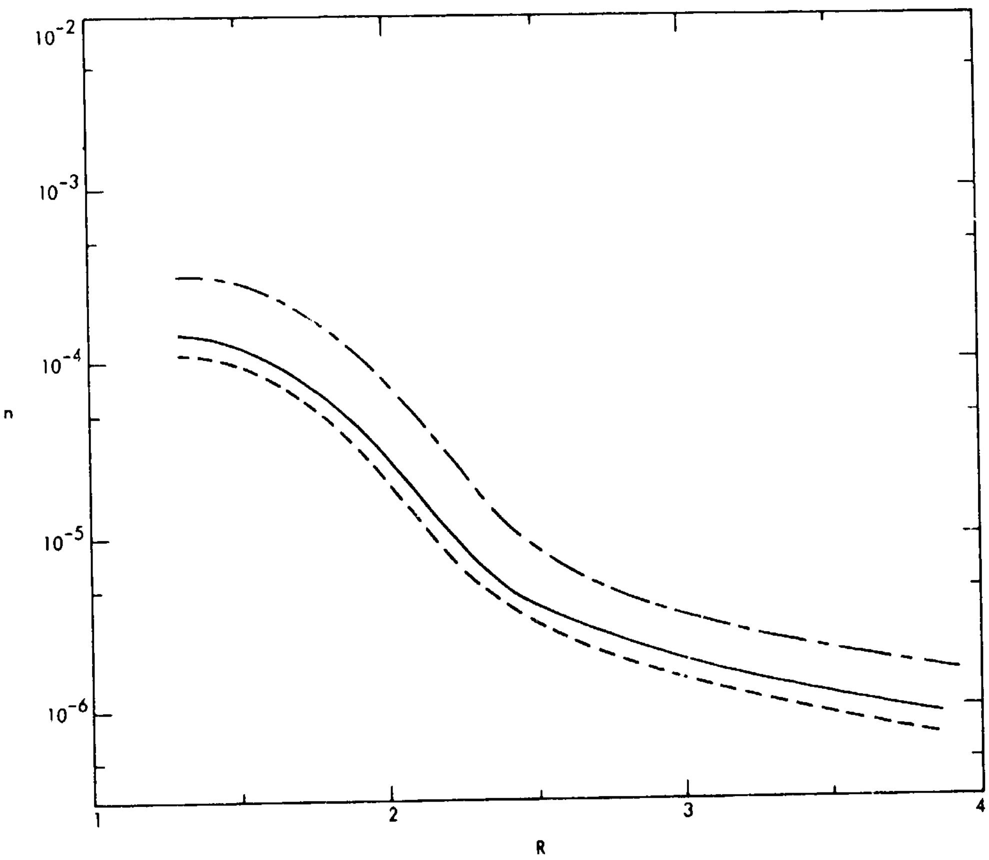

Figure 8. Equatorial number densities for flat orbit electrons at E_o's corresponding to B_o = 1 to 25 gauss. The dashed lines (--------) are densities for Berge's data raised 10%. The dashed lines (— — — —) are densities for Branson's data raised 19%

orders at five radii. Comparing the densities between the two P.A. distributions, it is apparent that the number of radiating electrons beyond three radii will be much more sensitive to the actual pitch angle distribution than to the magnetic field intensity.

For neither P.A. distribution did the number densities load the magnetic field. The maximum number of electrons/cc permitted are three to ten orders of magnitude above the computed densities.

C. *Radiative Half-Lives*

The radiative half-lives derived using isotropic and flat orbit pitch angle distributions are shown in Figures 9 and 10, respectively. For surface equatorial magnetic field intensities of around 7 gauss, the time increases as r^9 starting from six years at three radii. Half-lives of one year or less for both P.A. distributions run from the position of peak energy to planet limb. This indicates that the energy is limited by the life-time and that the injection or acceleration time is of the order of one year.

The errors in the numerical calculations are estimated to be around 5%. Radial and vertical shifts of the magnitude and position of the measured flux densities affect the derived quantities (energy, number density, half-life) through the function of the D's and the ratios of the D's. For results concerning the isotropic pitch angle distribution, the peak in average energy is very sensitive to modifications in the data above three radii. Results for flat helix electrons have been recalculated for uniform upward shifts of 10% in Berge's 70.4 cm data and 19% in Branson's 21 cm data. These results are shown in the appropriate figures.

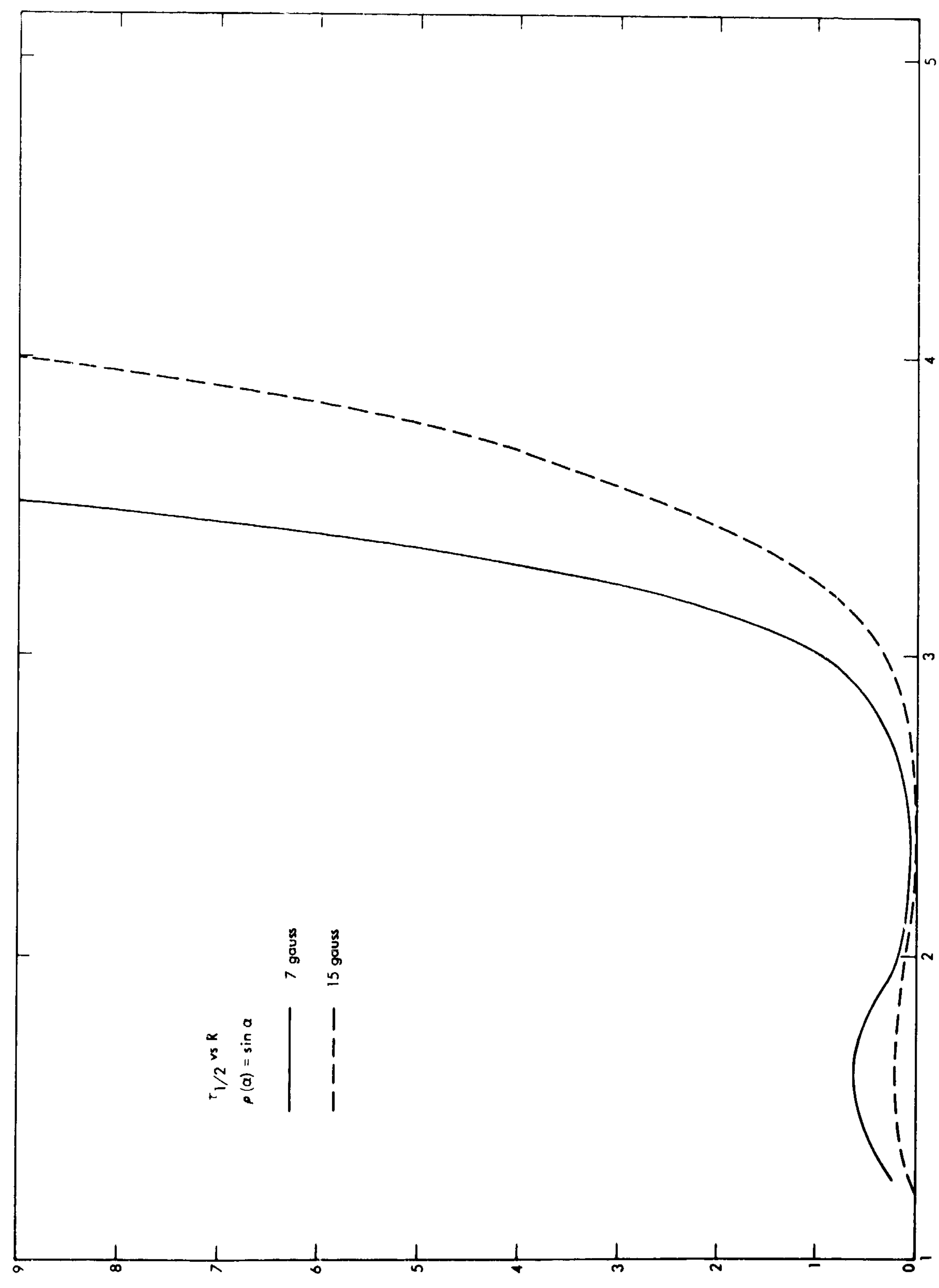

Figure 9. Equatorial half-lives for the isotropic P. A. case

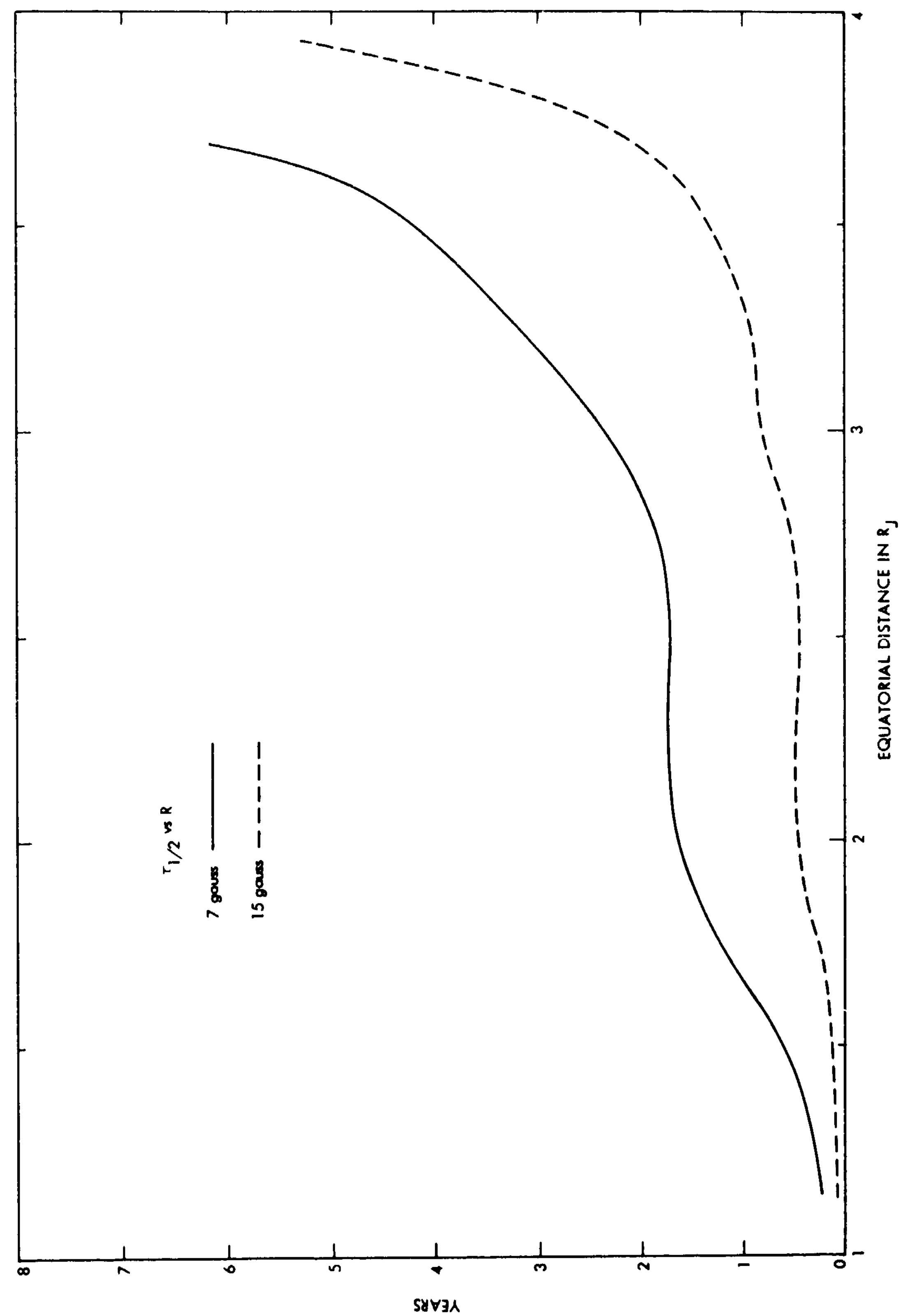

Figure 10. Equatorial half-lives for flat orbiting electrons

INTENSITIES AT 75 CM WAVELENGTH

Figure 11 shows the predicted 75 cm flux densities for the energies and number densities derived from both pitch angle distributions and B_0's of 7 to 25 gauss. These fluxes have been smoothed by a $\sin^2 x/x^2$ function with appropriate constants chosen to correspond with Branson's 80" arc half-power beam width resolution at 75 cm wavelength. The computed intensities for the isotropic P.A. distribution were virtually independent of magnetic field after smoothing.

Assuming the spectral index of equatorial emission is the same as for total emission, the best agreement with values given by Barber and Gower (1965) occurs at B_0 = 15 gauss for electrons in flat helices. On the same assumption, all intensities from isotropically distributed electrons would give spectral indices larger than -0.21.

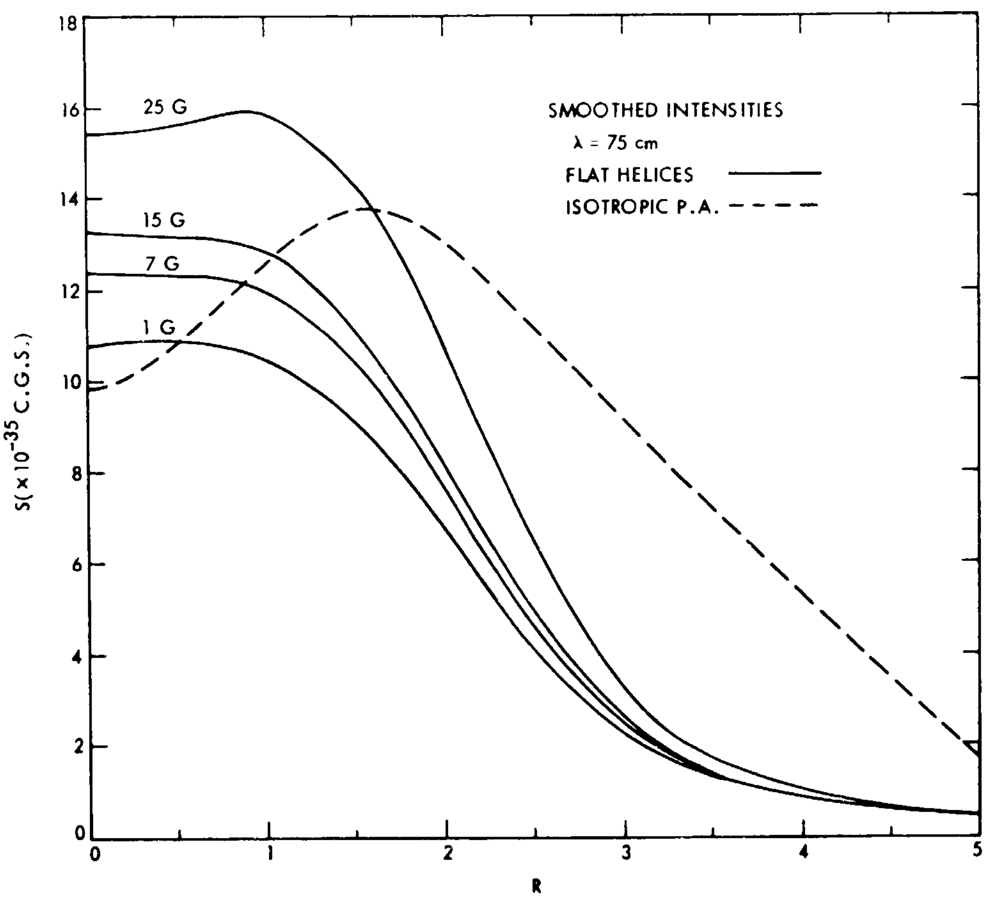

Figure 11. Smoothed 75 cm flux densities at 4.04 AU for E_0's and number densities corresponding to each B_0 used for flat orbiting electrons (solid lines) and the isotropic P. A. case (dashed line)

SUMMARY AND CONCLUSION

We have reduced the observations of Jupiter's decimeter radiation as a function of equatorial distance at 10.4 and 21 cms wavelength to source emission per unit volume of source electrons in each of 16 concentric rings about the planet's equator. The reduced observations in terms of emission/cc are shown in Figure 3. We assumed a Maxwell-Boltzmann electron energy distribution and obtained the electron temperature $F_0(r)$ which makes the ratio of the calculated electron radiation for the two wavelengths the same as the reduced observed radiation at the two wavelengths. The computed emission has been done for isotropic and flat orbit pitch angle distributions. If the assumptions are valid, the results for these two extreme cases should bracket the Jovian electron energy and number densities within the accuracy of the data.

The peak energies for isotropically distributed electrons exceeded the maximum energy for flat orbiting electrons, and the peaks were generally located from 2.25 to $3R_J$. The energies fell off as r^6 to r^8 below altitudes of the peak energy. The number densities ranged from 10^{-3} electrons/cc to 10^{-6}/cc with the smallest number for flat orbiting electrons in the equatorial plane. Beyond three radii, the order of magnitude on number density became a sensitive function of pitch angle distribution. In the limit of flat helices, the magnitude and radial dependence of the number densities were virtually independent of magnetic field and each corresponding E_0.

The total equatorial intensities at 75 cm wavelength were computed for $E_0(r)$ and $n(r)$ at different values of B_0. A good fit was obtained to observations at that wavelength for equatorial surface magnetic field intensities of 7 to 15 gauss in the limit of flat helices. This range is within similar estimates derived from decameter observations and other theoretical models.

The radiative half-life for electrons of initial energy E_0 in a dipole field was calculated and found to be nearly constant at one year or less for altitudes at and below the position in peak energy. The rapid decay in energy below the energy maximum and short, constant half-lives suggest that electron energy is limited by radiation loss and that injection or acceleration time is of the order of a year. The half-lives increase rapidly with r for r >2.5 to $3R_J$.

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DISCUSSION

DR. THORNE: It appears the densities you're coming up with are somewhat lower than the values which Davis and Chang published several years ago. The densities in their paper lay between 10^{-2} and 10^{-3}.

DR. LUTHEY: Yes, if a power law energy distribution is used, the number obtained is the total number of electrons when the computed power is compared with the observations. The total number of electrons times the power per electron gives the observed emission. Therefore, you have to assume some volume to contain the electrons. They (Davis and Chang) chose 10 Jupiter volumes.

DR. BEARD: Was this the electron density in the shell which would be higher than if you had attributed the radiation as coming from a very broad distribution of source? Would that possibly be the reason for the discrepancy?

DR. DAVIS: I'd have to look back.

DR. GULKIS: A number of things do worry me about the direct comparision of these two sets of data. First, I find it very surprising that the disk brightness temperatures at 10 and 20 centimeters are taken to be the same, despite the fact that both authors gave a number for it. This is likely to be true only if there is some additional source of opacity in the Jovian atmosphere like an ocean of water suddenly appearing at 250 degrees Kelvin. The atmospheric models suggest a very much larger brightness temperature (between 250 degrees and 350 degrees Kelvin) for the disk at 10 and 20 cm. Now, what this does is it affects the slope of the energy distribution on the near side of the planet.

The energy spectrum derived on the basis of the data at greater than 3 radii away is a very low signal to noise, and there's no mention made of what the signal to noise is there. The brightness contours, I think, of Glenn's data are probably less than 20 degrees--maybe 10 degrees out there. The same must also be true of the Branson data. So I'd say that at greater than 3 radii, we don't know what the tails of the distribution are doing. The signal-to-noise is not high enough.

Finally, although Branson observed an east-west polarization, the planet itself was not east-west, and they made a correction to the east-west polarization. I don't know how they made that correction.

DR. LUTHEY: He made two observations, one at 21 cm and simultaneously another one at 75 cm. At 21 cm, they used the feed-horns (polarized east-west), and for the 75 cm, they were polarized north-south.

DR. GULKIS: What about Faraday corrections?

DR. LUTHEY: Well, Faraday rotation won't be very much at 21 cm. He did correct for Faraday rotation at 75 cm, as I recall. No correction was made for the disc temperature at 75 cm because it is negligible at that wavelength. And, of course, there's no dip where the planet is. But the think I did notice about the emission curve is that the emission region, while it may not be more extensive than 4 radii, does appear larger for 75 cm wavelength than for 21 cm at around 4 radii. If you take a look at Branson's 21 cm data at 15 degrees longitude, compare that with Berge's data at 21 degrees longitude, you find that beyond 3 radii, the emission at 21 cm is also greater than the emission at 10.4 cm. That at least gives a lid on how energetic the electrons can be beyond 3 radii. It may not fall off as R^{-3}. It may go straight out, but it will be the order of the values I have shown.

DR. GULKIS: I still feel uncomfortable in accepting that without knowing what the signal-to-noise in those regions is.

DR. BEARD: The signal at 3 Jupiter radii is still pretty good.

DR. BERGE: I forgot how far it has fallen off by 3 R_J. Somewhere between 3 and 4, I would certainly lose confidence.

DR. WARWICK: I would strongly agree with Sam's (Gulkis') conclusion. The spread is in the direction that Joe (Luthey) mentioned, but the question is whether the difference between strip scans at 75 and 21 cm is significant or not. My instincts tell me that it's not.

DR. LUTHEY: Different in what respect?

DR. WARWICK: The one strip scan shows a contour which lies outside the other one.

DR. LUTHEY: The 21 cm data lies a little bit on and above it at the center.

DR. WARWICK: Right. The question is what does that mean. And it sounds to me as though it is conditioning your results more strongly than the experimental point justifies!

DR. LUTHEY: You could see more emission like that at 75 cm, depending on where you are on the power curve for a single electron. If you look at the power versus $1/E^2$, it goes up very sharply and then drops off exponentially as the energy goes from very large values to small values. Depending on which side of the peak you are on, you could get more emission at 21 cm than at 10 cm wavelength. The emission also depends on magnetic field intensity. As you move outward in the equatorial plane toward lower magnetic field intensities, you'll move across the peak of the emission curve. For the appropriate energy, you could have a region of large R where the emission at 21 cm exceeded that at 10 cm.

DR. BEARD: Judging from these dots at about 3 Jupiter radii, for instance, Branson's temperature contour is about a hundred and fifty degrees, and Berge's is about 60 degrees; by the time you get out to the 4, I think you're really "fighting."

DR. GULKIS: How do you explain the fact that the disk temperatures are the same at 10 and 20 cm?

DR. LUTHEY: Well, I don't (*explain it*). I just take the observationalists' word for it!

DR. BEARD: I had a computer program in which I calculate what the disk temperature was rather than taking 250 degrees, and we got one run with all the bugs out of the computer. We are getting disk temperatures for Branson that are comparable with what he infers the disk temperature is. For Berge's, I haven't succeeded in roughing that out yet, but it seems to be somewhat less, and I think that's a mistake in the data. We are determining the disk temperature, not from this, but just analyzing the pattern. The temperature might vary across the source of the planet that you've pointed out, as Berge pointed out, and as Branson pointed out, too. If you are, the idea is that you're seeing deeper into the planet, which might be a hotter region, and you'd expect that the center of the planet would then appear more hot because your optical depth....

DR. GULKIS: That turns out to be a small effect.

DR. BEARD: That's right.

DR. KENNEL: I noticed that you pointed out considerable variations between the flat helices case and the isotropic case, and I wondered if you considered parameterizing the pitch-angle distribution by the sine of the α^n and doing the same thing for the different powers of "n" to tell us whether or not the flat pitches are really singular case and go slightly off in degrees and get back to the isotropic. I'd like to know exactly how anisotropic your flat pitch results really apply.

DR. LUTHEY: No, I haven't parameterized for $\sin^n\alpha$ in the case for an exponential energy distribution. I have done it for the Davis and Chang model where they use the power law energy distribution, and then only for n = 2 and n = 5.

MR. THOMAS: You said that you used Westfold's '59 results for synchrotron radiation as a function of pitch angle, and my recollection is that those were corrected.

DR. LUTHEY: I showed the corrected form. Westfold has a sine α in the numerator, and it's only a factor of $1/\sin^2$, so it puts the sine α in the denominator. The assumption for these power formulas is that the pitch angle α is much, much greater than mc^2/E. So, for 0° pitch angle, you don't consider it.

MR. BECK: Could you say something about your estimates of the protons population?

DR. LUTHEY: I don't have any numbers on what the proton population would be. What I wanted to say about the protons was that looking at the E_0 curves in both cases for both pitch-angle distributions, it appeared that they came in according to the diffusion model and attained energies that I've indicated. Then they'd fall off, presumably because of radiation loss, and be turned over to the thermal plasma. However, a proton entering at the same point in the magnetosphere and also conserving the first adiabatic invariant would have comparable energies at 3 and 4 radii. Below 2-1/2 where the energy of the electrons begins to fall off quite rapidly, that would not happen to the protons because protons do not radiate until they get above BeV, at least that we would be able to see in any decimeter range.

The energetic protons would continue to diffuse in getting even more energetic below 3 radii until you finally get to the surface of the planet.

DR. WHITE: In your preprints, you speculated that this increase in protons you talked about would somehow interact with electrons to cause a loss. Are you still of this opinion?

DR. LUTHEY: If the densities of protons get very large very close to the planet, it could.

DR. WHITE: What is your opinion about the E_0 falling off as you get in close to the planet? Do you feel that's due to radiation, or do you feel that's due to the protons?

DR. LUTHEY: No, not the protons. I feel the falling off of the E_0 below 2-1/4 radii is due to the radiation loss. In the half-radius from 1-1/2 to 1r, we thought that effect of energy exchange between the two populations of protons and electrons would take effect.

DR. BEARD: The reason for suggesting that was because the half-life seemed to decrease to less than a year in the earlier work. So the suggestion was made that if the half-life is very much lower and if the particles come in from the outside, you'd expect the half-life to increase as you came nearer the planet. Instead, possibly it decreases. Then this is an alternative suggestion, that maybe there was some interchange between the high-energy protons and the electrons which would explain the decrease in half-life, where you would expect an increase in the half-life.

DR. WHITE: But now you feel that the synchrotron radiation isn't doing it?

DR. BEARD: No, we always felt that the synchrotron radiation did it, but we couldn't understand why the synchrotron radiation half-life should decrease as you came on into the planet. You would expect it to increase if the particles were coming in from the outside--they would take longer to get very close to the planet, not shorter than the time they take to get to, say, 2 Jupiter radii. How do you explain the decrease? Well, one possibility was that there was an energy exchange between the protons and the electrons close to the planet which would cause the half-life to decrease, because the electrons were getting energy faster than what you'd expect if they diffused in from the outside.

DR. WHITE: Well, I guess I don't quite understand. I would expect that the synchrotron lifetime is shorter as one gets in closer to the planet. That would control things, so I would expect that that would be the lifetime. I would expect a shorter lifetime, just as you pointed out.

DR. BEARD: You see, the lifetime is related to the injection mechanism. If you've got a half-life of a year, then the injection time must be of the order of a year. Therefore, as you get in closer to the planet, you'd expect longer lifetimes, because the injection time would be longer if the particles were coming in from the outside. It's easier to get to 2 Jupiter radii than 1 Jupiter radii.

DR. WHITE: The way I would argue is that the equilibrium flux is dependent upon how fast they come in by diffusion and how fast they're lost by synchrotron radiation, and synchrotron radiation would be the controlling factor, because it drops off so fast as one gets in close. So, the equilibrium intensity would drop down if the diffusion source was not able to furnish enough until the point where one could get an equilibrium.

DR. BEARD: In that case, anything that you saw close to the planet--if it were slower--would have a very long half-life because it has to be around there a long time before it was replensihed.

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ELECTRON AND PROTON FLUX MODELS FOR JUPITER'S RADIATION BELTS

David A. Klopp*

INTRODUCTION

The "models" reported here are estimates of the energetic particle distribution in Jupiter's radiation belts. They were developed early in 1970 as part of a preliminary study of a Jupiter orbiter mission and provided some insight into the tradeoffs involved in selecting orbits for such a mission. They were not intended to serve as a theoretical basis for the interpretation of observed decametric or decimetric radiation but rather as engineering "guesstimates" permitting a more realistic comparison of alternative mission modes.

ESTIMATES OF ELECTRON AND PROTON FLUXES

An early estimate of the trapped electron density near Jupiter was provided by Chang and Davis (1962) who interpreted the observed decimetric emission as synchrotron radiation from relativistic electrons. If the radiation is emitted from a volume ten times that of Jupiter, and if the electrons are subject to a uniform magnetic field of one gauss, Chang and Davis estimated an electron density of 2×10^{-3} electrons/cm^3, corresponding to an electron flux of about 6×10^7 electrons/cm^2-sec.

Eggen (1967) examined the available literature and concluded that an electron flux on the order of 10^7 electrons/cm^2-sec in the equatorial region of 2.5 to 3 R_J would be consistent with speculation of most observers. Eggen assumed an inner edge at about 2.5 R_J, and estimated fluxes at higher altitudes by scaling from the Earth's radiation belts using the ratio of the magnetic fields (the Jovian field was taken as one gauss at 3 R_J). Using the same scaling parameter, Eggen estimated the Jovian proton population by scaling up the Earth's low-energy proton flux.

**IIT Research Institute, 10 W. 35th St., Chicago, Illinois 60616.*

By considering particle precipitation due to pitch angle diffusion, Kennel and Petschek (1966) derived an upper limit to the Earth's equatorial omnidirectional trapped electron flux due to electrons of energy greater than 40 keV as

$$\phi\,(>40\ \text{keV}) \approx \frac{7 \times 10^{10}}{L^4}\ \text{electrons/cm}^2\text{-sec} \qquad (1)$$

where L is the McIlwain parameter (here equal to the planetocentric radius in units of Earth radii). Haffner (1969) applied the scaling parameter B_0/L^3, where B_0 is the equatorial field strength at the planet's surface, and generalized this result to

$$\phi\,(>E) \approx \frac{3.5 \times 10^{11}\ N\ B_0^{4/3}}{L^4}\ e^{-E/E_0} \qquad (2)$$

which assumes an energy spectrum of the form $exp(-E/E_0)$. The variable N is introduced to account for the degree of saturation, i.e., the limiting flux corresponds to N equal unity. Haffner takes the characteristic energy E_0 as $3L^{-1.36}$ MeV at Earth and generalizes this to

$$E_0 \approx \frac{5.25\ B_0^{0.455}}{L^{1.36}}\ \text{MeV} \qquad (3)$$

by using the scaling parameter B_0/L^3 as before.

A comparison of Haffner's estimates with that of Eggen, for equatorial electron fluxes at Jupiter due to electrons of energy higher than 3.4 MeV, is given in Figure 1. As will be discussed below, electrons of these energies will penetrate aluminum thicknesses corresponding to slightly more than two gm/cm^2. The estimates ascribed to Haffner in Figure 1 are based on his suggested values for B_0, N, and a (the effective inner radius of the electron belt).

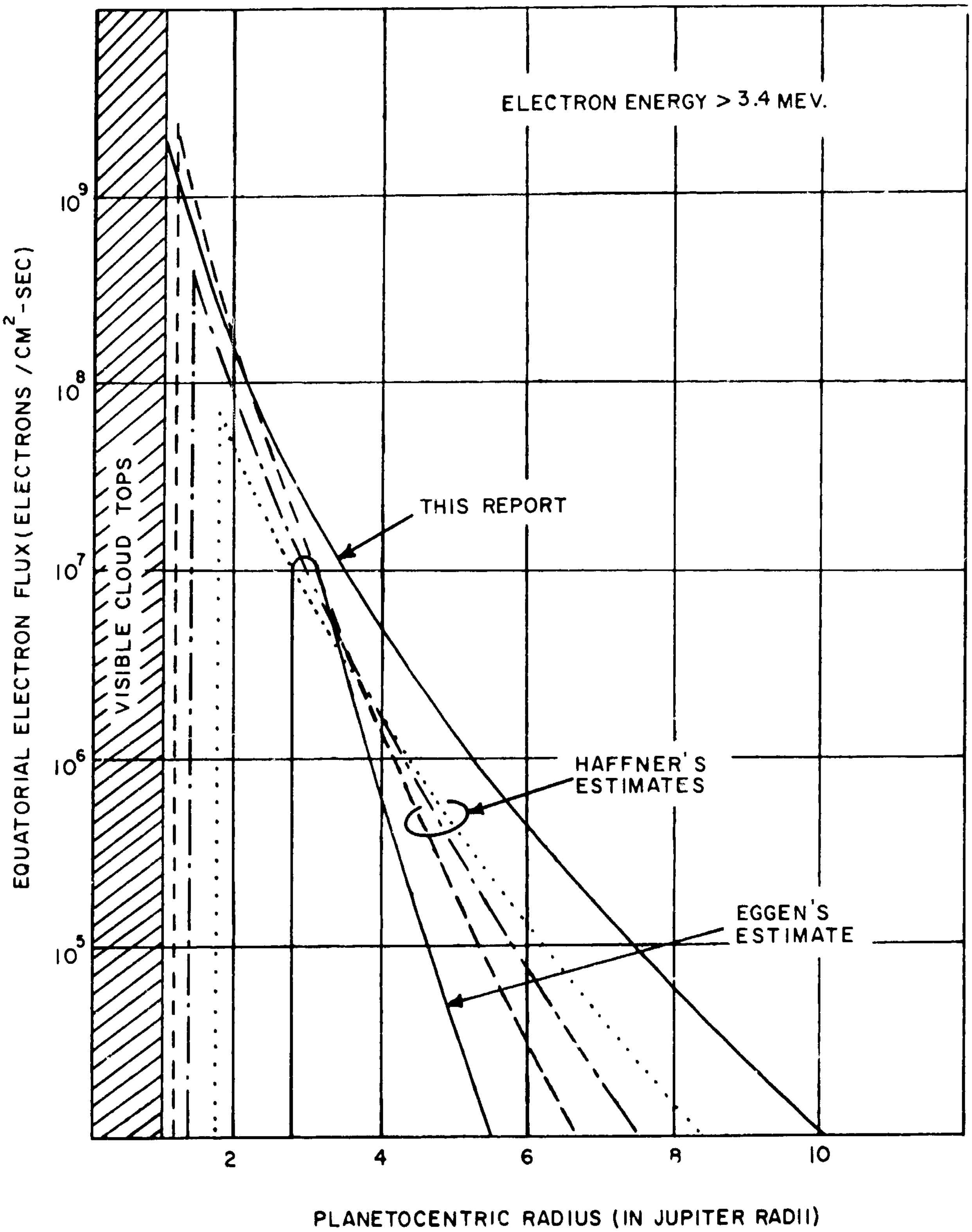

Figure 1. Electron Fluxes in Jupiter Radiation Belt Models

Although use of the scaling parameter B_0/L^3 might be appropriate when applied to the electron energy spectrum, it need not be applied to equation 1. A more direct procedure is available. Kennel and Petschek show that

$$\phi\left(>E_R\right) = \frac{\left(1 - \frac{w}{\Omega}\right)\left(\frac{c}{\pi^2 e R_E}\right)}{A - \frac{1}{\left(\frac{\Omega}{w}\right) - 1}}\left(\frac{B \; \ell n \; G}{\ell}\right) \tag{4}$$

where the resonant energy is

$$E_R = \left(\frac{B^2}{8\pi n}\right)\left(\frac{\Omega}{w}\right)\left(1 - \frac{w}{\Omega}\right)^3 \tag{5}$$

in which $(B^2/8\pi n)$ is the magnetic energy per electron, w is the whistler frequency, and Ω is the electron gyrofrequency. In equation 4, c is the speed of light, e the electron charge, R_E the radius of the Earth, A the degree of pitch-angle anisotropy, B the field strength, G the gain on one wave traversal of the active region along a field line necessary to balance the whistler wave loss due to reflection at the ionosphere, and ℓ is the effective length of the field line in Earth radii. For 10 MeV electrons in a one-gauss field, supposedly typical of the situation at Jupiter, the gyrofrequency is about one MHz. The whistler frequency is on the order of a kHz, so that $w/\Omega \ll 1$ (also appropriate in the Earth case), and equation 4 reduces to

$$\phi\left(>E_R\right) \approx \frac{c}{A\pi^2 e R_E}\left(\frac{B \; \ell n \; G}{\ell}\right) \tag{6}$$

Kennel and Petschek estimate $\frac{\ell n \; G}{\ell}$ as about 3/L and suggest that A is typically 1/6. Then

$$\phi\left(>E_R\right) \approx \frac{18 \; c \; B_0}{\pi^2 e R_E L^4} \tag{7}$$

since B equals B_0/L^3. Substitution of appropriate numerical values yields the result previously given by equation 1. It is presumed here that equation 7 applies to Jupiter if R_E is replaced by R_J.

The Jovian magnetic field intensity is not well known. Eggen reports that estimates based on polarization measurements and radio source intensity yield values between 0.17 and 17 gauss at 3 R_J. Hide (1966) has suggested a magnetic moment of about 8×10^{30} emu, which corresponds to a surface equatorial field of about 22 gauss. Using this value for B_0, and accepting Haffner's model for the energy spectrum, the electron flux is taken as

$$\phi\,(>E) \sim \frac{3.5 \times 10^{11}\,N}{L^4}\,e^{-E/E_0} \tag{8}$$

where now E_0 is 21.4 $L^{-1.36}$ MeV and the $3.5 \times 10^{11}\,L^{-4}$ follows from equation 7. This expression implies that at 3 R_J the total electron flux is 4.3×10^9 N, corresponding to an electron density of 0.14 N for relativistic electrons. By equating this result to the Chang and Davis estimate of 2×10^{-3} electrons/cm^3, N must be on the order of one percent. Thus, the equatorial omnidirectional flux at Jupiter is estimated to be

$$\phi\,(>E) \sim \frac{3.5 \times 10^{9}}{L^4}\,e^{-E/E_0}\ \text{electrons/cm}^2\text{-sec} \tag{9}$$

Estimates of the flux above 3.4 MeV obtained in this manner are shown in Figure 1.

Equation 9 is assumed to apply down to L equal one, corresponding to the visible surface of Jupiter. That is, pitch-angle diffusion is assumed to be the only loss process. There may be significant radiative loss due to synchrotron emission, but it will be suggested below that there are no significant upper atmospheric loss processes, at least, not as seen in the Earth's belts.

It is generally agreed that electrons are lost from the inner edge of the Earth's radiation belt by coulomb scattering into the loss cone. For multiple coulomb scattering, the mean square angular deviation θ^2

$$\theta^2 = \frac{8\pi ND\,z^2\,Z^2\,e^4}{p^2\,v^2}\,\ell n\,\frac{a_0\,pv}{2Z^{4/3}\,ze^2} \tag{10}$$

where

N = nuclear density (nuclei/cm^3)

D = traversed thickness

z = atomic number of incident particle

Z = atomic number of scattering nucleus

e = electron charge

p = relativistic momentum of incident particle

v = incident particle velocity

a_o = Bohr radius (5.29×10^{-9} cm)

Of course, the density and type of the scattering nuclei vary with altitude. In the Earth's case, assuming a medium-density atmosphere representative of average conditions (Johnson, 1965), hydrogen is the dominant constituent above 2,500 km, helium from 1,000 to 2,500 km, and oxygen from about 300 to 1,000 km. If it is assumed that scattering through an angle of 0.5 radians will place the electron velocity within the loss cone (Hess, 1968) and that 10^5 seconds (about 30 hours) represents a reasonable lifetime estimate, the scattering nuclei density required for significant loss of trapped electrons is:

$$N \approx \frac{10^{-5}\ p^2}{32\pi\ Z^2\ e^4\ \ln\left(\frac{a_o\ pv}{2Z^{4/3}\ e^2}\right)} \qquad (11)$$

The right-hand side is now a function only of electron energy and the type of scattering nuclei.

Assuming an electron energy of 300 keV for inner zone electrons in the Earth's Van Allen belts, the required nuclear densities are

gaseous elements	atoms/cm^3
hydrogen.	5×10^6
helium	1×10^6
oxygen	1×10^5

These results indicate that neither hydrogen nor helium scattering contribute to electron losses, since the observed densities are about 10^4 atoms/cm^3 for hydrogen and about 10^5 atoms/cm^3 for helium. On the other hand, at about 1,000 km altitude, the observed average oxygen density is about 10^5 atoms/cm^3. Thus, those electrons whose mirror-point is at an alitutde of 1,000 km or less will be quickly lost from the radiation belts. Hence, the inner edge of the Earth's electron belt is estimated to occur at about 1.15 R_E which is in rough agreement with the observed data.

A similar analysis may be applied to the electron belts at Jupiter. Using equation 9, it is found that at L=1, one-half of the electron flux is due to electrons of energy >15 MeV; the other half is due to electrons <15 MeV. That is, the median electron energy is about 15 MeV. Using equation 11, evaluated for 15 MeV electrons, the atom densities required for electron loss are:

gaseous elements	atoms/cm^3
hydrogen.	3×10^9
helium	8×10^8

Gross and Rasool (1964) have estimated the hydrogen atom density above the visible surface of Jupiter, assuming a hydrogen/helium ratio of 10. Their results indicate a peak hydrogen density of 5×10^9 atoms/cm^3 at 250 km altitude. The peak helium density is 2.5×10^8 atoms/cm^3. The density estimates fall off quickly with altitude, N_H reaching about 10^9 at 300 km altitude. It appears that those electrons having mirror points above about 300 km will not be lost rapidly due to scattering.

Kennel and Petschek note that equation 4 is equally applicable to protons. Their results show that, for the Earth, the observed proton flux is approximately equal to the limiting flux for L>4, but at L<4, the observed flux is roughly a factor of ten less than the limiting flux. Following the same procedure used in arriving at equation 9, the Jupiter proton flux due to protons of energy >E is:

$$\phi\,(>E) \sim \frac{3.5 \times 10^9}{L^4}\, e^{-E/E_0} \text{ protons/cm}^2\text{-sec} \qquad (12)$$

where N has been taken as 0.01, by analogy with the electron flux. It should be emphasized that no measurements are available from which an appropriate value of N for protons may be deduced, unlike the degree of electron saturation which is based on the observed decimeter radiation from Jupiter.

Haffner has suggested that, for protons,

$$E_0 \doteq \frac{3{,}000\, B_0^{5/3}}{L^5} \text{ MeV} \qquad (13)$$

Assuming that (for Jupiter) B_0 is 22 gauss, this expression yields

$$E_0 \doteq \frac{520 \text{ BeV}}{L^5}$$

Although it is difficult to imagine what acceleration process might result in protons of 500 BeV energy at Jupiter, the field energy density is capable of trapping such particles. It is suggested here that an $1/L^3$ energy dependence, characteristic of radial diffusion based on violation of the third adiabatic invariant, provides a more reasonable basis for speculation on the energies of Jovian protons. That is, the characteristic energy for protons is taken as

$$E_0 \sim \frac{27\, B_0}{L^3} \text{ MeV} \qquad (14)$$

The numerical coefficient has been fixed by assuming an E_0 of 1 MeV at L=2 for the Earth's proton belts. Thus, for a Jovian surface field of 22 gauss, the proton E_0 is taken as about 600 MeV/L^3. (Note that this implies an energy of about 5 keV at 50 R_J).

Figure 2 compares estimates of the equatorial proton flux at Jupiter for protons of energies greater than 40.6 MeV. This cutoff energy is

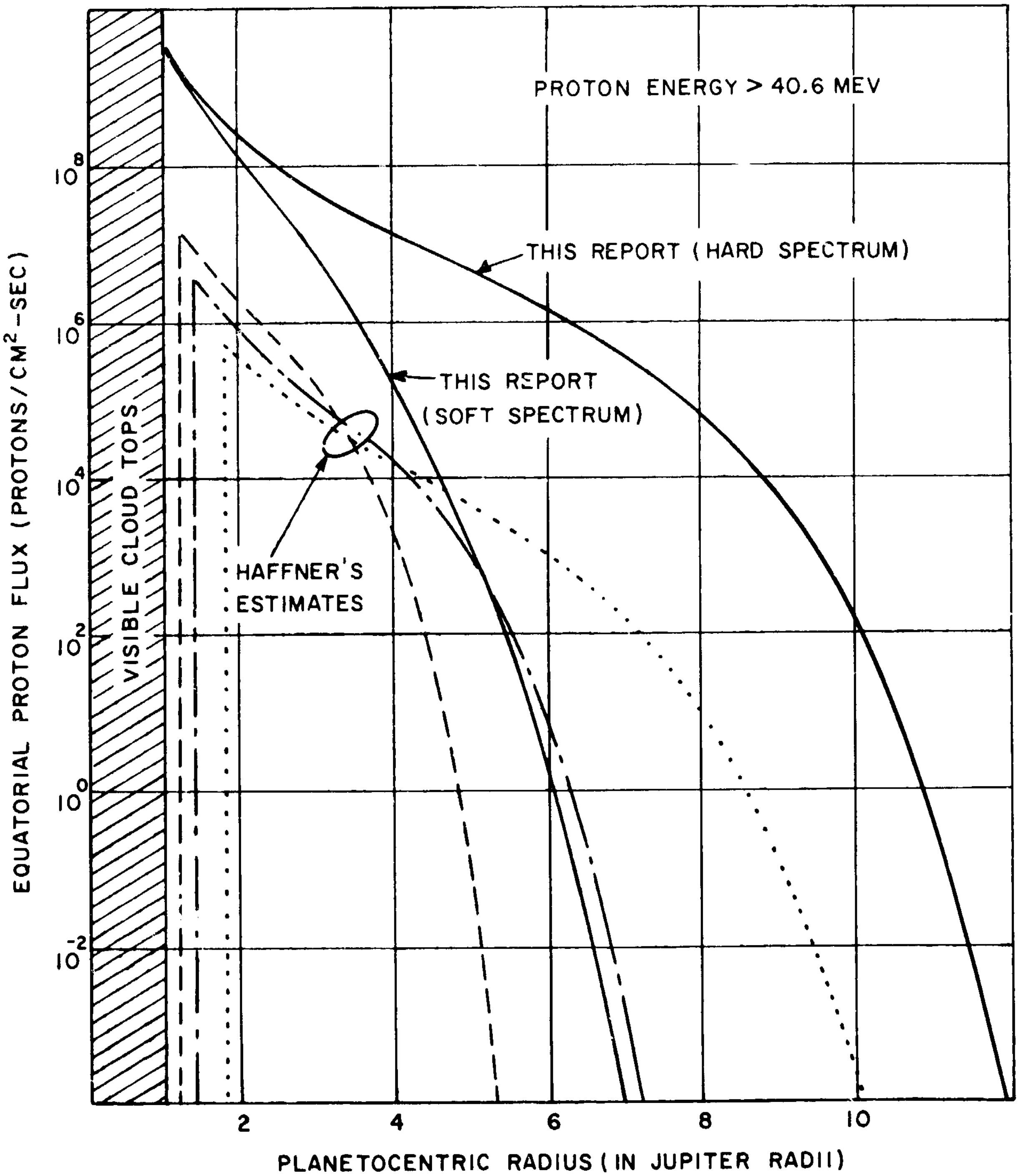

Figure 2. Proton Fluxes in Jupiter Radiation Belt Models

appropriate to an aluminum thickness of 2 gm/cm^2. The solid curves are based on the use of equation 12, but two different assumptions have been made concerning the characteristic energy E_0. The estimate identified by "hard spectrum" in the figure arises from taking E_0 equal to $520/L^5$ BeV, while that identified by "soft spectrum" is based on an E_0 of $600/L^3$ MeV. At low L values, the estimates tend to agree, since most of the flux is more energetic than 40 MeV (the cutoff energy).

No inner edge is shown to the proton fluxes suggested here. As with electrons, upper atmospheric scattering does not appear to provide a loss mechanism for Jovian protons. At the Earth, high energy protons are thought to be removed from the belts by slowing down to about 100 keV as a result of collisions with oxygen nuclei. Below 100 keV, the protons enter into charge-exchange collisions with hydrogen. An analogous loss process does not appear likely at Jupiter, since the upper atmosphere is presumed to be hydrogen and helium, neither species being very effective in slowing down high-energy protons.

In summary, the equatorial charged particle fluxes in the radiation belts surrounding Jupiter may be estimated according to

$$\phi\ (>E) \simeq \frac{3.5 \times 10^9}{L^4}\ e^{-E/E_0}\ \text{particles/cm}^2\text{-sec} \qquad (15)$$

where

$$E_0 \simeq \begin{cases} \dfrac{21.4}{L^{1.36}}\ \text{MeV for electrons} \\ \\ \dfrac{600}{L^3}\ \text{MeV for protons} \end{cases} \qquad (16)$$

It may be noted that the flux per unit energy is

$$\phi\ (E) \simeq \frac{3.5 \times 10^9}{E_0 L^4}\ e^{-E/E_0}\ \text{particles/MeV-cm}^2\text{-sec} \qquad (17)$$

ESTIMATED DOSE RATES

For electrons normally incident upon a plane shield of equivalent thickness X, usually expressed in units of g/cm^2, the plane shield acts as a filter, blocking out electrons of energy $<E_c$, but transmitting electrons of energy $>E_c$. The shield cutoff energy E_c is approximately given by[1]:

$$E \doteq \frac{2.8X^{0.9+0.065 \ln X}}{Z^{0.2}} \text{ Mev} \tag{18}$$

where X is the shield thickness (g/cm^2) and Z is the atomic number of the shield material. Thus, the cutoff energy corresponding to 1 and 2 g/cm^2 of aluminum shielding is 1.7 and 3.2 MeV, respectively.

The electron flux-to-dose conversion factor is approximately[1a]

$$C = 3 \times 10^{-8} \frac{\text{rad - cm}^2}{\text{electron}} \tag{19}$$

which is independent of electron energy, at least for the energy range of interest here. Since the flux-to-dose conversion factor is constant, the energy spectrum of electron emerging from the shield may be ignored. The dose rate due to electrons is then approximately

$$D_e \doteq \frac{3.8 \times 10^5}{L^4} e^{-E_c/E_o} \text{ rads/hr} \tag{20}$$

using equation 15, provided that the flux is normally incident upon the shield.

Burrell (1964) has noted that for oblique incidence, the slab layer of thickness X should be replaced by the thickness along the slant path

$$\rho = \frac{X}{\cos \theta_o} \tag{21}$$

[1] *Haffner, 1969*

[1a] *Haffner, 1967*

where θ_0 is the angle between the slab normal and the angle of incidence. Thus, the dose rate due to an isotropic flux incident upon a slab of thickness X is

$$D_{iso} = 2\pi \int_0^1 \frac{1}{4\pi} D\left(\frac{X}{\cos\theta}\right) d(\cos\theta) \tag{22}$$

where D is a function of X/cos θ, through E_c, and of course, L. Burrell has suggested that the required integration may be approximated by

$$D_{iso} = \frac{1}{2N} \sum_{i=1}^{N} D\left(\frac{X}{\cos\theta_i}\right) \tag{23}$$

where

$$\cos\theta_i = \left(\frac{1}{N}\right)(i-\tfrac{1}{2}) \tag{24}$$

This numerical integration scheme, with N=10 (that is, cos θ_i= 0.05, 0.15, 0.25,..., 0.95) has been employed to estimate the dose rate due to electrons (with the results shown in Figure 3). Two equivalent shield thicknesses (1 and 2 g/cm^2 of aluminum) have been used. Moderate amounts of shielding are not very effective at low values of L because the electron energy is high. Also shown for comparison are Haffner's estimates (Haffner, 1969) of the electron dose rates. Although Haffner's fluxes are somewhat lower than those estimated using equation 15 (see Figure 1), his dose rates are somewhat higher than those estimated here, because he has regarded the flux as normally incident upon the shield.

A similar procedure may be used to estimate proton dose rates. For an aluminum shield of thickness X g/cm^2, the proton cutoff energy in MeV is (Burrell, 1964)

$$E_c = \left(\frac{X}{0.00274}\right)^{0.562} \tag{25}$$

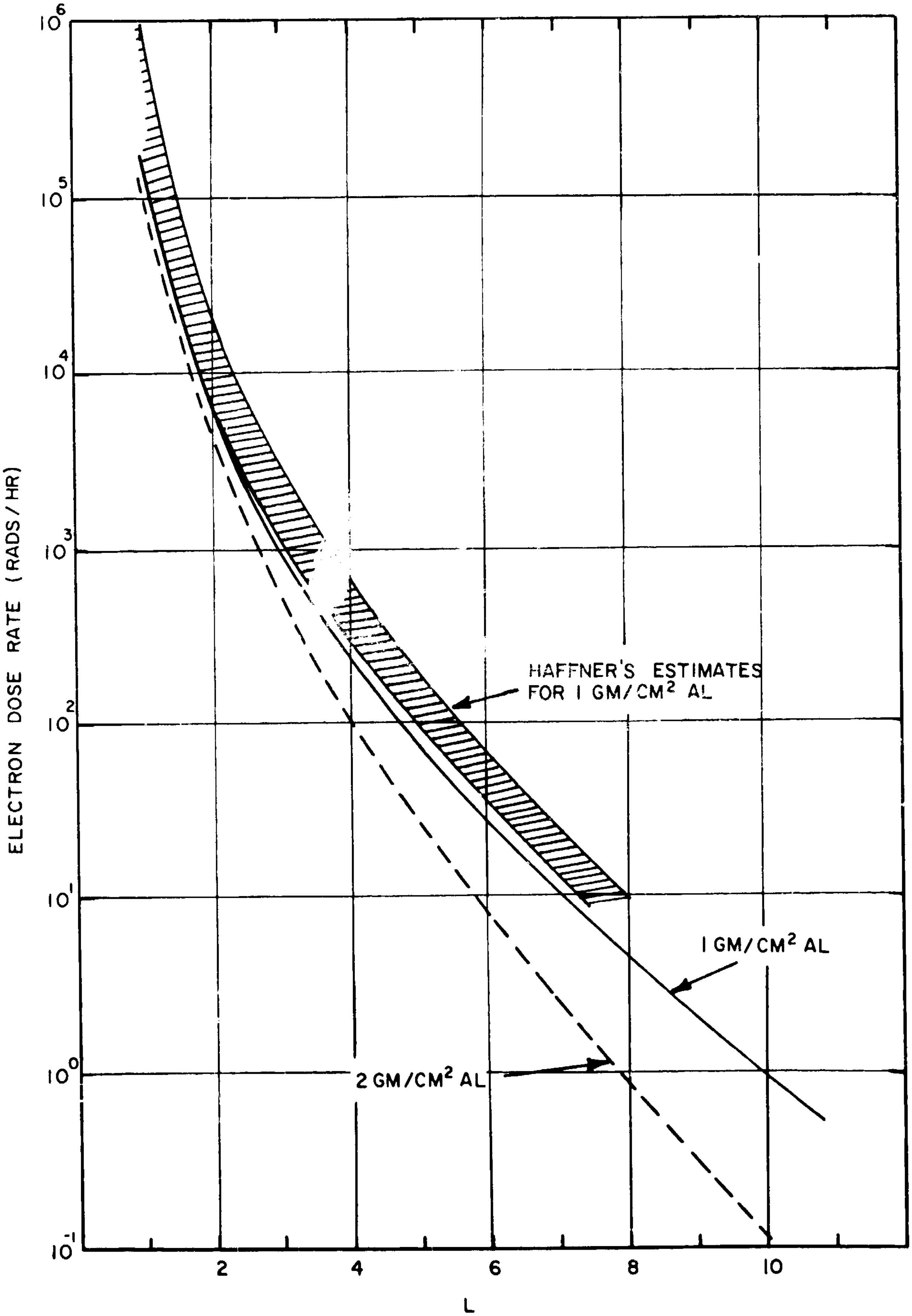

Figure 3. Shielded Electron Dose Rates

while the flux-to-dose conversion factor is

$$C(E) = 4.58 \times 10^{-6} \left(E^{-0.8} + 4.55 \times 10^{6} E\right) \frac{\text{rads-cm}^2}{\text{protons}} \tag{26}$$

It is important to note that the flux-to-dose conversion factor is now dependent upon the particle energy after passing through the shield, unlike the case with electrons. It is, therefore, necessary to consider the energy spectrum of protons emerging from the shield. If a proton of energy E is incident upon an aluminum shield of thickness X, the energy upon emerging from the shield is approximately (Burrell, 1964)

$$E^* \simeq \left(E^{1.78} - \frac{X}{0.00274}\right)^{0.562} \tag{27}$$

assuming that E is greater than E_c, the shield cutoff energy. Thus, the proton dose rate is

$$D_p = 2\pi \int_0^1 \int_{E_c}^{\infty} \frac{1}{4\pi} \Phi\,(E,L)\; C(E^*)\; dE\; d(\cos\theta) \tag{28}$$

where the flux has been given earlier by equation 15 (see Figure 2).

The angular integration may be treated as described above for electrons. The energy integration has been treated by using a five-group proton energy distribution. That is, for a given X, the shield cutoff energy is computed according to equation 25. A 1 g/cm^2 aluminum shield will screen out all protons of energy less than 27.5 MeV, while a 2 g/cm^2 shield will screen out protons less than 40.6 MeV. The proton energy spectrum above the cutoff energy is then divided into five energy groups such that the proton flux in each energy group is approximately one-fifth of the total proton flux above the cutoff energy. The protons in each energy group are then considered to be isotropically incident upon the shield with an energy equal to the average energy of the protons in that energy group. The dose rate is computed for each energy group (assuming that all the protons in each energy group are characterized by an energy E* computed from equation 27) with the incident energy equal to the group-averaged incident energy. The total proton dose rate is simply the sum of the dose rates for each energy group.

This procedure results in the proton dose rate estimates shown in Figure 4. As before, the "hard spectrum" results are based on a proton characteristic energy of $520/L^5$ BeV, while the "soft spectrum" results are based on a $600/L^3$ MeV characteristic energy. It is believed that the "soft spectrum" results are more realistic. In both cases, the solid curves pertain to 1 g/cm^2 of aluminum shielding; the dashed curves to 2 g/cm^2 of aluminum shielding. Also shown for comparison are Haffner's estimates of the proton dose rate. For the *soft spectrum* case, it appears that moderate amounts of shielding are ineffective at L values about <3, as was the case with electrons. It may also be noted that at altitudes lower than 3 R_J (i.e., L=4), the proton dose rate ("soft spectrum") is higher than the electron dose rate. That is, for low-altitude orbiters, the proton flux is more hazardous than the electron flux.

ESTIMATED RADIATION LIFETIMES

The total radiation dose experienced by an orbiting spacecraft is simply the sum of the electron and proton dose rates integrated over the mission duration. Since the orbit radius can be expressed analytically, it is convenient to have an analytic approximation to the dose rate results presented above. Approximate dose rates are provided by taking

$$\ell n\ D_1 = \begin{cases} 15.81 - 2.858\ L + 0.1471\ L^2 - 0.00197\ L^3 & \text{for } L \leq 2 \\ 17.53 - 4.090\ L + 0.3629\ L^2 - 0.01295\ L^3 & \text{for } L > 2 \end{cases}$$

$$\ell n\ D_2 = \begin{cases} 16.27 - 3.496\ L + 0.2337\ L^2 - 0.00685\ L^3 & \text{for } L \leq 2 \\ 19.27 - 5.622\ L + 0.6241\ L^2 - 0.02766\ L^3 & \text{for } L > 2 \end{cases}$$

where D_i is the sum of the electron and proton ("soft spectrum") dose rates in rads/hr for aluminum shielding of i g/cm^2. These approximations are within 10%

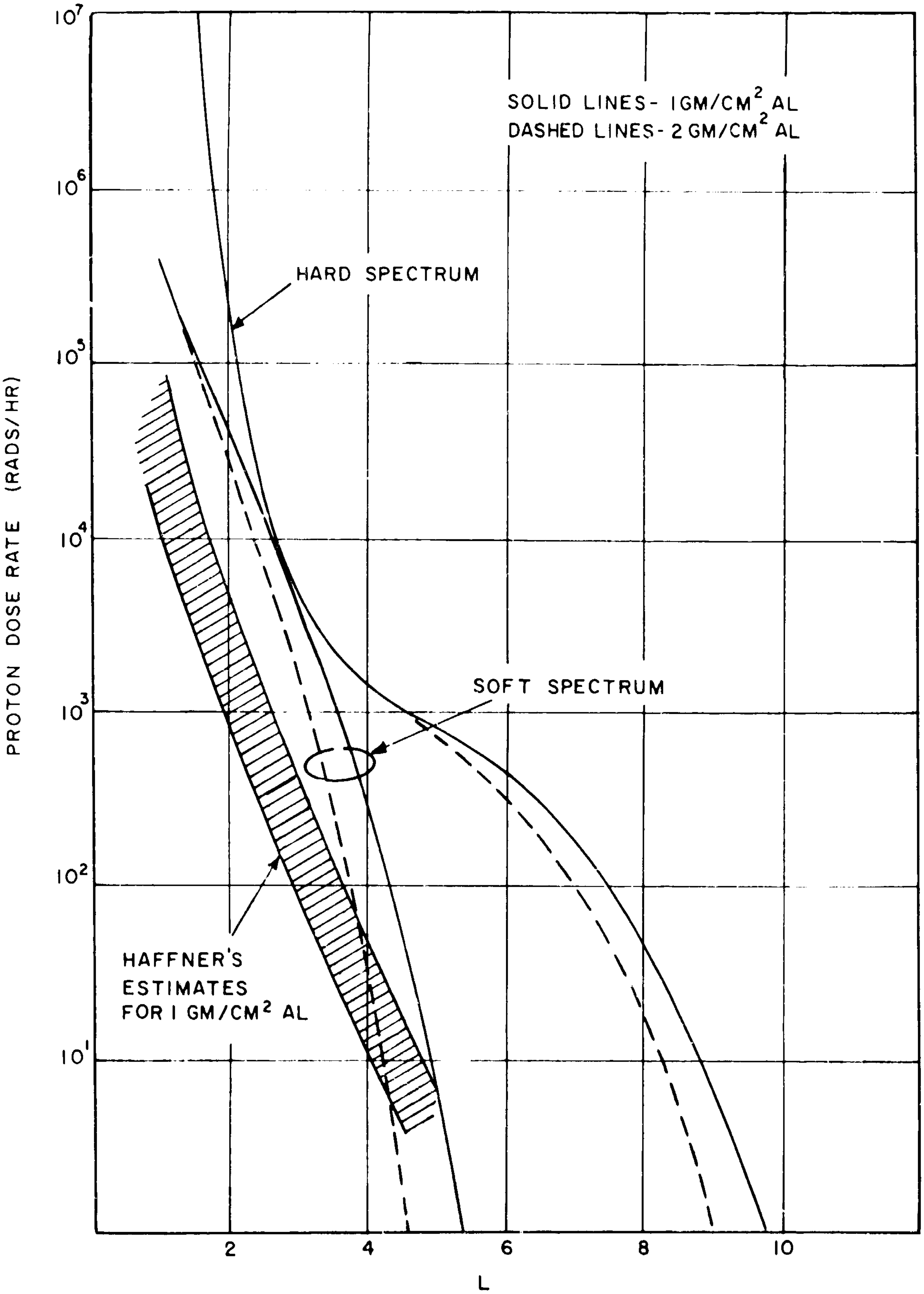

Figure 4. Shielded Proton Dose Rates

of the results shown in Figures 3 and 4 for $L < 2$. For L values between 2 and 10, the errors can be as large as 30%. Beyond $L=10$, the errors are unimportant since the dose rate is small. These approximate formulas have been used in estimating dose and lifetime data. The other important factor is an estimate of the maximum allowable dose.

Recent reviews (West et al., 1969; Reid, 1969) suggest that the most *vulnerable* spacecraft components are electronic circuits. Reid reports that silicon integrated circuits begin to fail after an integrated flux of about 10^{15} electrons/cm^2. Using the electron flux-to-dose conversion factor given above, this is equivalent to about 3×10^7 rads. Duberg and Hulten (1969) noted that at least some types of MOS devices show less than a one-third loss in gain after exposure to 3.4×10^{13} 128-MeV protons/cm^2 (3.3×10^6 rads), or 5.3×10^{13} 22-Mev protons/cm^2 (2.1×10^7 rads). These data suggest that a *maximum* permissible dose value useful for preliminary mission analysis might be as large as 10^7 rads. The radiation lifetimes presented here are based on this value. It should be noted that the radiation lifetime is inversly proportional to the maximum permissible dose, so that the lifetime can be easily adjusted if some other value is preferred for the maximum dose.

Figure 5 shows estimated radiation lifetimes as a function of orbital periapsis radius with the apoapsis radius as a parameter, assuming a 10^7 rad dose and 1 g/cm^2 of aluminum shielding. Circular orbits of 2 R_J altitude provide only a four-month spacecraft lifetime. Lower periapsis altitudes can be achieved without shortening the lifetime only by going to elliptical orbits. Although increasing the orbital eccentricity lengthens the radiation lifetime (for a fixed periapsis altitude), the orbital period also increases. That is, the number of orbital passes which can be made does not increase as rapidly as the lifetime, and in fact approaches some asymptotic value dependent upon the periapsis altitude. This effect is clearly shown in Figure 6. Thus, going from a 3×3 orbit to a 3×50 orbit will increase the radiation lifetimes from 117 to 17,000 days (a factor of 145), but the number of orbits completed increases from 180 to only 1,000 (a factor of <6). Figures 7 and 8 present similar data, except that the shielding's thickness has been increased from 1 to 2 g/cm^2 of aluminum. By comparing the data to Figures 5 and 6, it can be seen that moderate amounts of shielding are likely to be effective for periapsis altitudes higher than about 2 R_J, but are ineffective for periapsis altitudes lower than that. For example, the four-month lifetime of a 3 × 3 orbit can be increased to nearly 10 months by increasing the shielding from 1 to 2 g/cm^2 of aluminum. On the other hand, low-altitude missions are insensitive to the amount of shielding because of the high proton energies of the inner portions of the belts. Thus, the 105-day life of a 1.1 × 20 orbit can be increased to only 135 days by doubling the shielding from 1 to 2 g/cm^2.

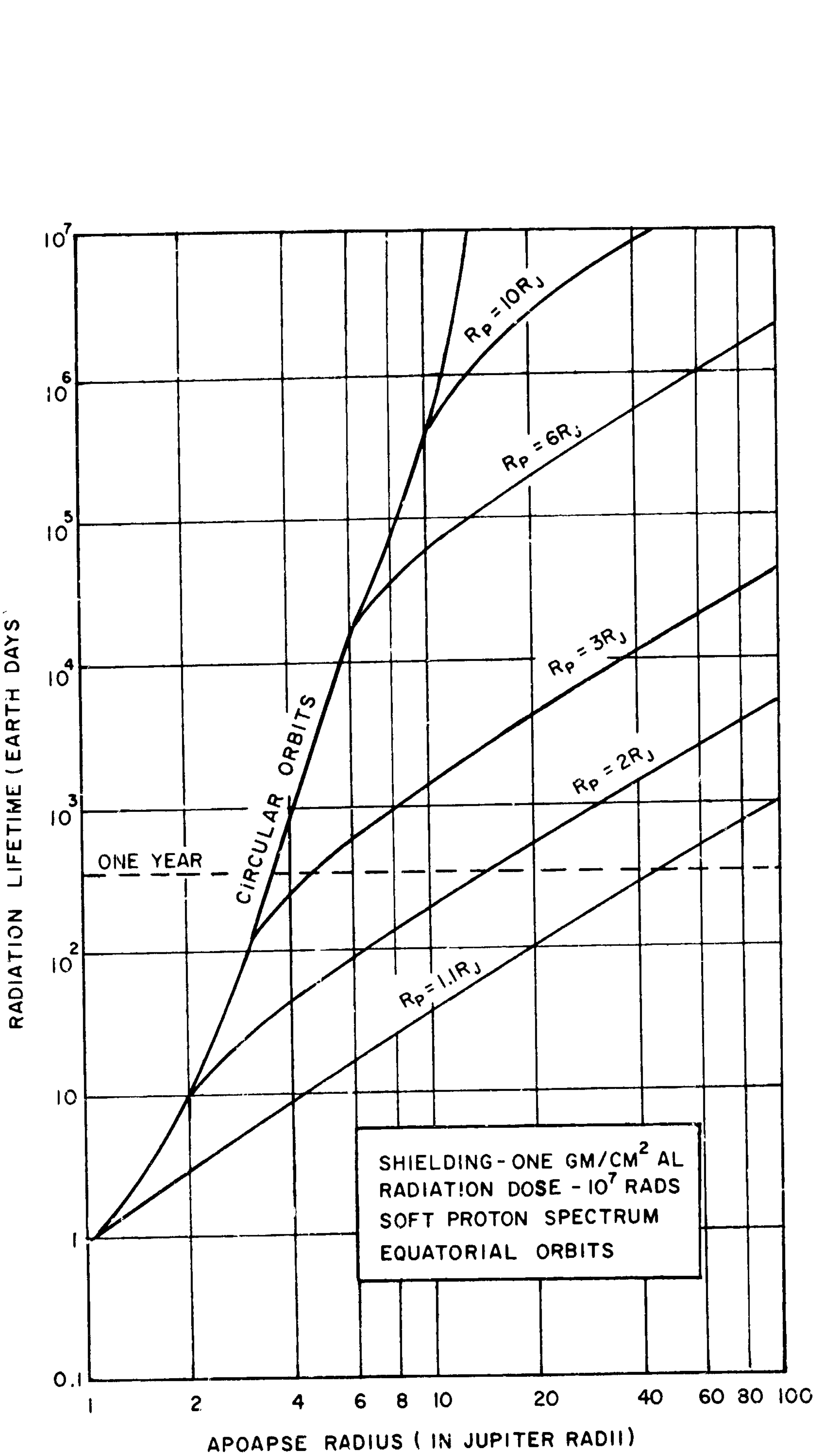

Figure 5. Lifetime in Days Behind 1 g/cm^2 Shield

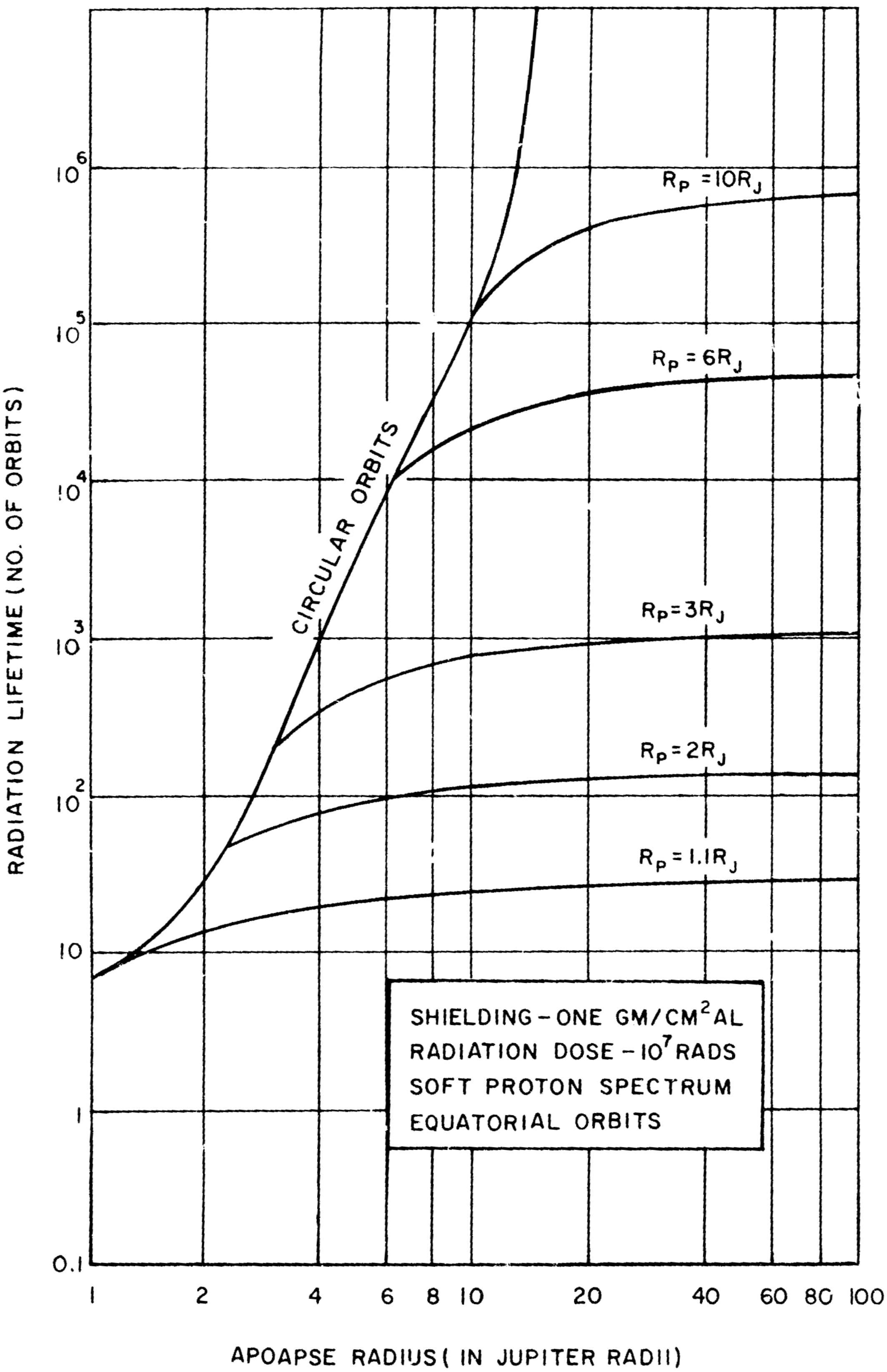

Figure 6. Lifetime (number of orbits) Behind 1 g/cm^2 Shield

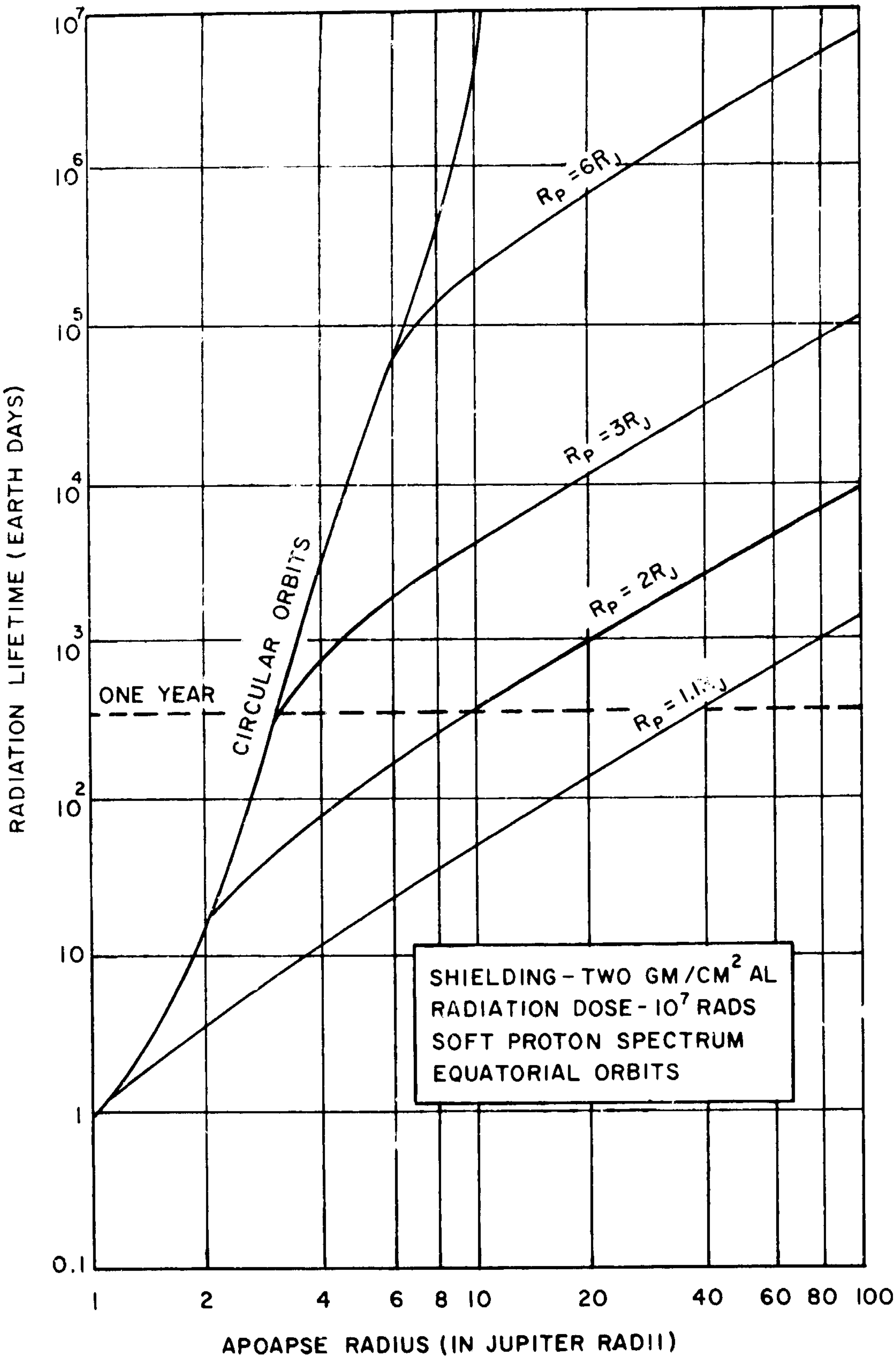

Figure 7. Lifetime on Days Behind 2 g/cm^2 Shield

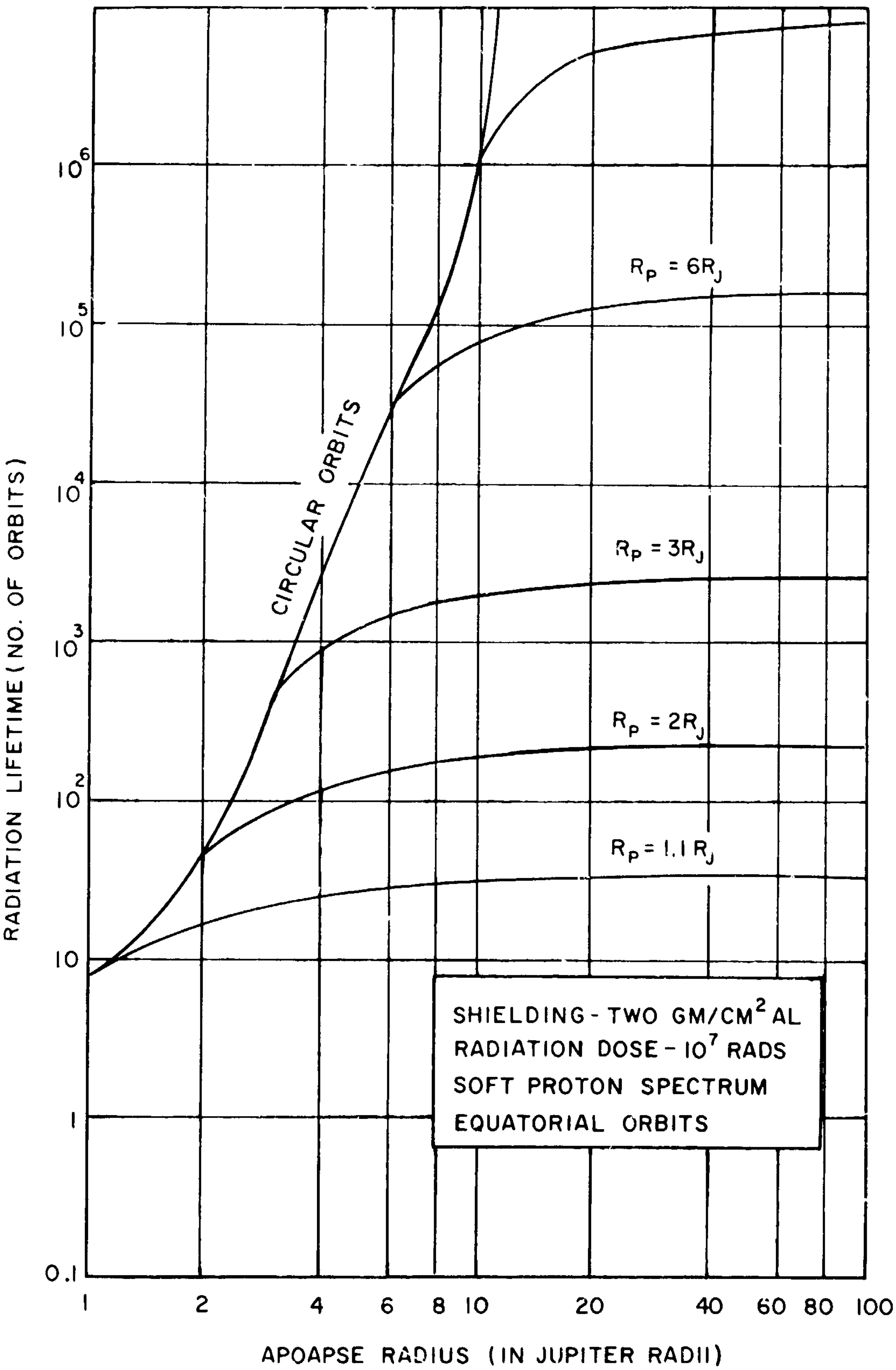

Figure 8. Lifetime (number of orbits) Behind 2 g/cm^2 Shield

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DISCUSSION

MR. PARKER: Did you consider displacement damage at all, or was it strictly ionization damage that led you to the limit of 10^7 rads?

MR. KLOPP: For the origin of 10^7 rads, we looked at some experiments with electronic circuits. We found that if one is skillful at circuit design, one can tolerate a dose of nearly 10^7 rads. Since we were talking about missions in 1981 or 1982, we felt free to increase that somewhat.

DR. BEARD: Did you take into account the possibility that the proton energy would decrease very rapidly as you went out, or did you assume a constant proton spectrum?

MR. KLOPP: E_0 falls off as L^{-3}. That's a somewhat slower falloff than Dr. Haffner used. On the other hand, our energy close to the surface was lower than Dr. Haffner's, so it tends to compensate, perhaps.

DR. TRAINOR: A comment on your choice of 10^7 rads. You'll find that many of the experiments are more sensitive than the electronics, and you will have lost them before the electronics dies.

MR. KLOPP: I'm sure that's the case with some experiments.

DR. TRAINOR: A gram per square centimeter is quite a penalty to pay. You probably can't afford that with the launch vehicles we've got now.

MR. KLOPP: That gets very specific, because now you're having to talk about spececraft design in some detail. It's hard to design a spacecraft which won't provide something on the order of a half a gram per square centimeter, depending upon where your instrument is located.

DR. TRAINOR: I was thinking previously from the point of view of instruments. Most of those science instruments tend to get put on outboard experiment platforms.

MR. KLOPP: You have to bear that in mind.

I did want to make one other comment. We talked only about equatorial orbits here, and I'd like to point out that's not as uninteresting to the analysts as you might think. Many people have talked about doing combined Jupiter-Galilean satellite missions where you do, in fact, want an orbital plane which is roughly in the equatorial plane. So, equatorial orbits are of definite interest to the analysts.

SCIENTIFIC AND ENGINEERING ANALYSES OF JUPITER'S ENERGETIC ELECTRONS AND PROTONS*

Neil Divine**

INTRODUCTION

Activities at JPL in support of the Thermoelectric Outer Planet Spacecraft (TOPS) and Jupiter Orbiter Studies have indicated the need for an understanding of the potential impact of the charged particle populations in Jupiter's magnetosphere on spacecraft intended to operate there. The following brief review supplements the reviews of this environment included in the appropriate NASA Space Vehicle Design Criteria Monograph (ref. 1), which supported its development, and in ref. 2. The implications for spacecraft intended to function near Jupiter are summarized in references 3 and 4.

BASES OF THE MODELS

Properties of the electron population are inferred from UHF (decimetric) radio data observed at the Earth and interpreted as synchrotron radiation generated by relativistic electrons trapped in Jupiter's magnetic field. Details of the magnetic field conclusions, the UHF data sets, and the theoretical synchrotron radiation descriptions employed are summarized below for several published and unpublished analyses. Properties of the proton population are based entirely on theoretical or analogy considerations (notably the presence of both electrons and protons in the Earth's radiation belts).

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** *Jet Propulsion Laboratory, Pasadena, California 91103.*

SPECIFIC MODELS FOR ELECTRONS

The electron models described below are summarized in figure 1. In addition to the dependence there shown on magnetic shell parameter L (here $L = R/R_J(\cos\phi)^2$, where R/R_J is the jovicentric distance in units of Jupiter's radius R_J), distributions with energy E, latitude ϕ, and/or pitch angle α are important parts of many of the models discussed.

Barber and Gower (ref. 5) base their results on their own flux density measurements at 49 cm (610 MHz), assuming a field strength of 1 gauss in the emitting region, a critical frequency of 3000 MHz, and a total UHF power of 10^9 watts. They employ a rough estimate of the emission volume and the synchrotron formulae of Chang and Davis (ref. 6). The electron energy is estimated at 10 MeV (nearly monoenergetic), the pitch angle distribution is described as flat, and no latitude distribution is specified for their order-of-magnitude description.

Branson (ref. 7) bases his results on his own aperture synthesis maps of the radiation at 21 cm, assuming a field strength of 10 gauss at the surface. Model-fitting is employed in the form of a sum of thin radiating shells, for which appropriate Stokes parameters have been calculated by Ortwein et al. (ref. 8). The differential energy spectrum is proportional to E^{-1} between 1 and 30 MeV, the differential pitch-angle distribution is proportional to $\sin\alpha$ for $\alpha_L < \alpha < 90°$, and no latitude distribution is described.

Carr and Gulkis (ref. 9) results are in every respect similar to those of Barber and Gower (ref. 5), except that the frequency of the broad emission maximum taken at 850 MHz leads to an energy of 14 MeV, and that the synchrotron formulae of Ginzburg and Syrovatskii (ref. 10) have been used.

Chang and Davis (ref. 6) apply their own development of the synchrotron theory to the data obtained by several observers at various UHF wavelengths, summed to yield a total power of 2.8×10^{16} erg/sec at wavelengths greater than 3 cm. They derive several cases, but the one shown in figure 1 is based on a local field strength of 1 gauss and a differential energy spectrum

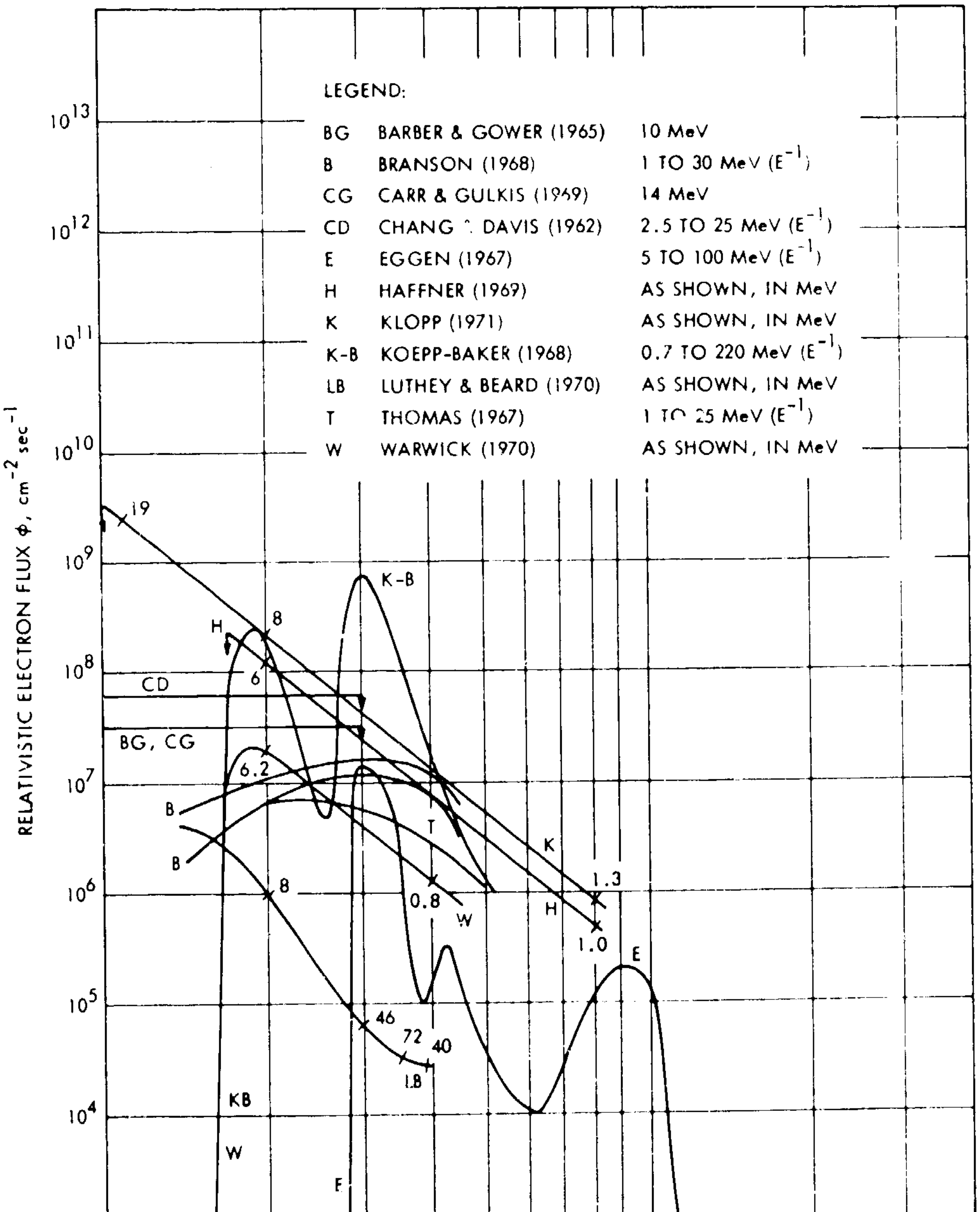

Figure 1. Jupiter Electron Models in Equatorial Plane

proportional to E^{-1} between 2.5 and 25 MeV. They further conclude that the linear polarization evidenced in the data requires that the distribution of pitch angles be sharply peaked near $\alpha = 90°$.

Clarke (ref. 11) specifies six thick-shelled models in considerable detail, each intended to yield Stokes' parameter values which mimic the aperture synthesis maps of Branson (ref. 7) at 21 cm. The synchrotron formulae of Ortwein et al. (ref. 8) and circular polarization analysis of Legg and Westfold (ref. 12) were used. Although a differential energy spectrum proportional to E^{-1} is intended, limiting energies are not specified; for this reason none of Clarke's models are plotted in figure 1. Each model includes two shells, one nearly isotropic and the other highly beamed in pitch-angle; the latitude distributions can be inferred from the pitch-angle specifications.

Eggen (ref. 13) bases his peak flux estimate on the consensus of a number of radioastronomers, and his distributions with L and α on scaling from the Earth's radiation belts. He further specifies a differential energy spectrum proportional to E^{-1} between 5 and 100 MeV. The three peaks in the distribution with L (see figure 1) result from the Earth analogy, and are artificial as respects Jupiter; the innermost peak is sharper and farther from the planet than would be suggested by more recent data (ref. 7).

Haffner (ref. 14) bases his distributions on the scaling of the limits set by ion cyclotron resonance instability (ref. 15) from Earth to Jupiter; in this generalization the relation between magnetic field strength and magnetic shell parameter L is preserved. The distributions are normalized such that the synchrotron radiation from the belts, calculated according to the formulae of reference 16 and isotropically radiated, matches the observed flux density from Jupiter. The peak electron flux shown in figure 1 is correspondingly higher than other estimates because the others have included observed radiation beaming. Further, the distribution shown there is calculated for an equatorial surface magnetic field strength of 12 gauss, within the range specified by ref. 14. Latitude and pitch-angle distributions are not specified thoroughly, but the energy distribution is Maxwell-Boltzmann, with characteristic energy proportional to $L^{-1.36}$.

Klopp (ref. 17) employs a technique very similar to Haffner's (ref. 14), although the scaling is carried out somewhat differently. The equatorial surface magnetic field used is 22 gauss, and the isotropic assumption is retained, leading to fluxes and energies similar to Haffner's; the fluxes are higher than in other analyses. Latitude and pitch-angle distributions are not specified.

Koepp-Baker (ref. 18) bases his flux values on a preliminary aperture synthesis map at 10.4 cm, to which the Stokes parameters predicted according to the formulae of Thorne (ref. 19) are matched, using two belts modeled on Earth distributions. The equatorial surface magnetic field is taken as 15 gauss. The differential energy spectrum is proportional to E^{-1} for energies between 0.7 and 220 MeV, and simple latitude and pitch-angle distributions are specified as well.

Luthey and Beard (ref. 20) base their flux values on the comparison of strip scans which represent the east-west dependences of the 10.4 and 21 cm maps of Berge (ref. 21) and Branson (ref. 7). The ratio of the intensities at the two wavelengths yields the local characteristic energy, whereas the absolute intensity yields the local electron flux. The theory used is that of Schwinger (ref. 22). The case plotted in figure 1 is ref. 20's case i, for which the equatorial magnetic field strength is 7 gauss. Although the analysis is sophisticated, the numerical results are suspect because the resolution of the data does not warrant point-by-point comparisons, because the two data sets are not directly comparable (ref. 23), and because there is a possibly unstable numerical differentiation of the published data implied in the technique used to obtain the distributions with L. Modifications to these models are in progress (ref. 24). Latitude distributions are not specified.

Thomas (ref. 25) bases his calculations on 10.4 cm data published by Berge (ref. 21) and on the synchrotron radiation description from reference 8. The differential energy spectrum is proportional to E^{-1} for

3/10

energies between 1 and 25 MeV. Latitude and pitch-angle distributions are not specified.

Warwick (ref. 26) bases his considerations on the UHF bandwidth (taken as approximately 3600 MHz), a magnetic field of 2 gauss at L = 1.8, and a synchrotron brightness temperature of 183°K over the disk at 21 cm (data from ref. 7). He develops his own simplified synchrotron formulae, which agree satisfactorily with those of other sources cited. Having used the above to set the levels at the flux peak, Warwick applies L-shell diffusion theory (as worked out in ref. 27) to set the flux and energy elsewhere. He feels that the consequent relations to values for solar wind electrons at the boundary of Jupiter's magnetosphere provide satisfactory confirmation for this mechanism. The energy distribution is not specified, but should be peaked about a local characteristic energy. The latitude distribution has a cutoff near 45°.

MONOGRAPH ELECTRON MODELS

These models are shown in figure 2 (same scales as fig. 1), and are thoroughly described in references 1 and 2. The nominal electron model is identical to Warwick's (ref. 26) except that the energy and latitude distributions are carefully specified, and the model energies and concentrations are uniform for $L \leq 2$. For $L \geq 2$, the latter two are proportional to L^{-3} and L^{-4}, respectively. For $L \leq 2$, the upper limit model exceeds the nominal model by uncertainty factors of 3 in the concentration and energy separately, in order to reflect uncertainties in the magnetic field, the UHF beaming, the UHF bandwidth, the synchrotron theory approximations, and the possibility of flux peaks sharper than those indicated by the data of limited resolution. For $L \geq 2$, the local energy and concentration are proportional to L^{-1} and L^{-2}, to reflect the increased uncertainties away from the observed flux peak. The upper limit models envelope all the models described in the foregoing section except those based on isotropic intensity assumptions or on preliminary data. These nominal and upper limit models are the ones which have been used in JPL's evaluation of the radiation hazard to spacecraft.

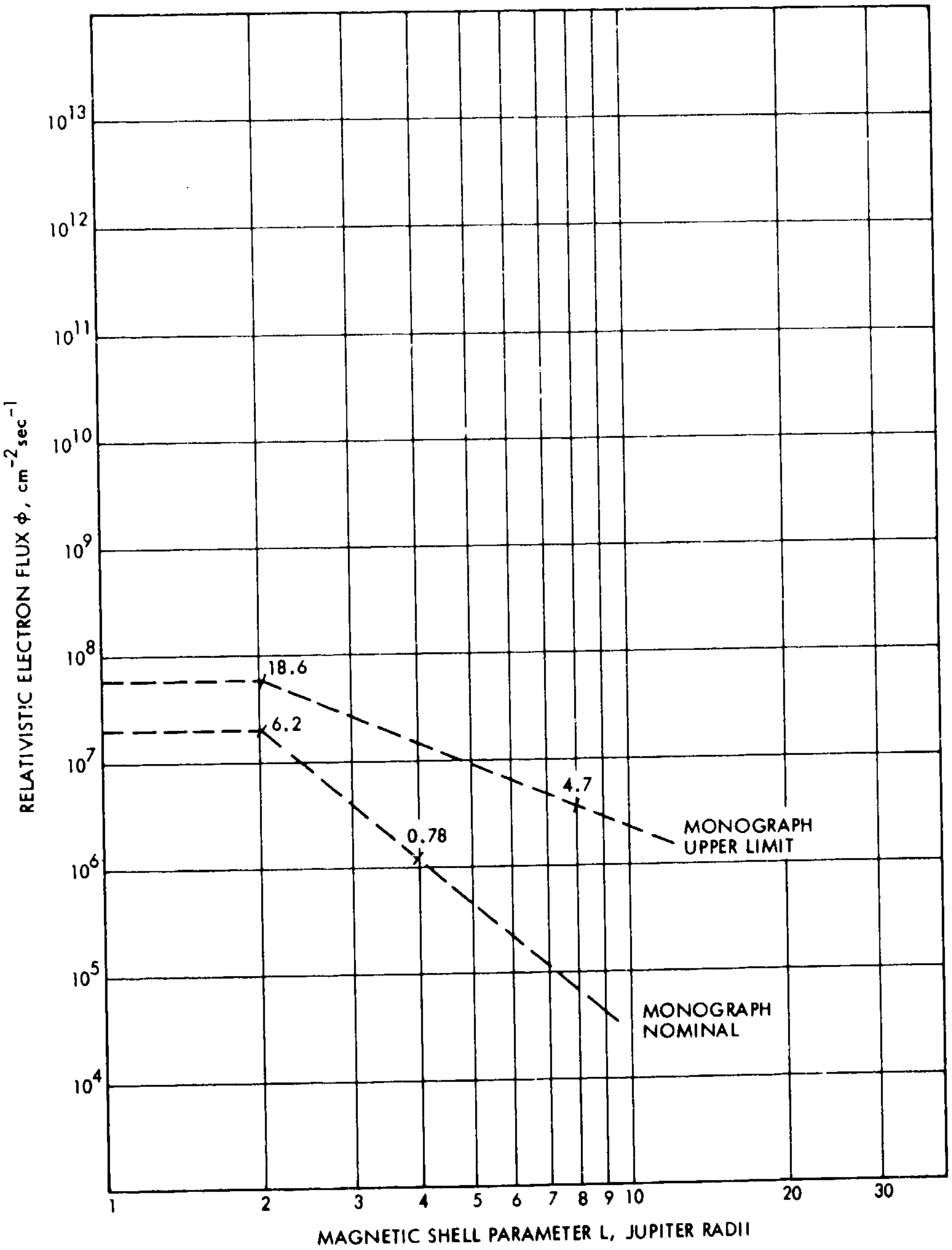

Figure 2. Electron Fluxes in the Monograph Models (local characteristic energies are shown in MeV)

SPECIFIC MODELS FOR PROTONS

The proton models are summarized in figure 3. None are based directly on Jupiter data, as no known data are applicable. Those from references 13, 14, 17, and 18 are simply scaled according to techniques already mentioned for electrons. The energies and flux levels which result are so diverse that one has little confidence in the validity of the considerations employed.

One basic physical consideration which has been suggested is that the energy density of the protons be limited to the energy density of the magnetic field in which they are trapped, or to some small fraction thereof. For comparison purposes, one such limit, for protons of 100 MeV energy, is shown in figure 3. Luthey and Beard (ref. 20) explain their expectation that the population nearly saturates this limit, in the absence of loss mechanisms (e.g., radiation, which affects electrons but not protons). They calculate the energy on the basis of conservation of the first adiabatic invariant (magnetic moment of gyration, proportional to the field strength) for protons diffusing inward from the solar wind. The local energies and fluxes suggested on this basis are shown in figure 3.

Thomas (ref. 25) suggests that Cosmic Ray Albedo Neutron Decay (CRAND) could be responsible for protons in Jupiter's radiation belts. His comparison of circumstances at the Earth (for which this mechanism is thought to be an important source of inner zone protons) and at Jupiter leads to a uniform flux of 100 to 1000 MeV protons for $L \leq 18$, as diagrammed in figure 3.

Warwick (ref. 26) suggests that L-shell diffusion is an appropriate mechanism for protons at Jupiter, just as it is for the Earth's outer zone protons and for Jupiter's electrons (see foregoing discussion of ref. 26's electron model). The energies can be set simply (see second paragraph of this section), and the number concentrations are the same as for the electrons (determined from the UHF data and diffusion theory). An error in the published version of reference 26 places the flux too low throughout by about a factor of 3, as shown in figure 3.

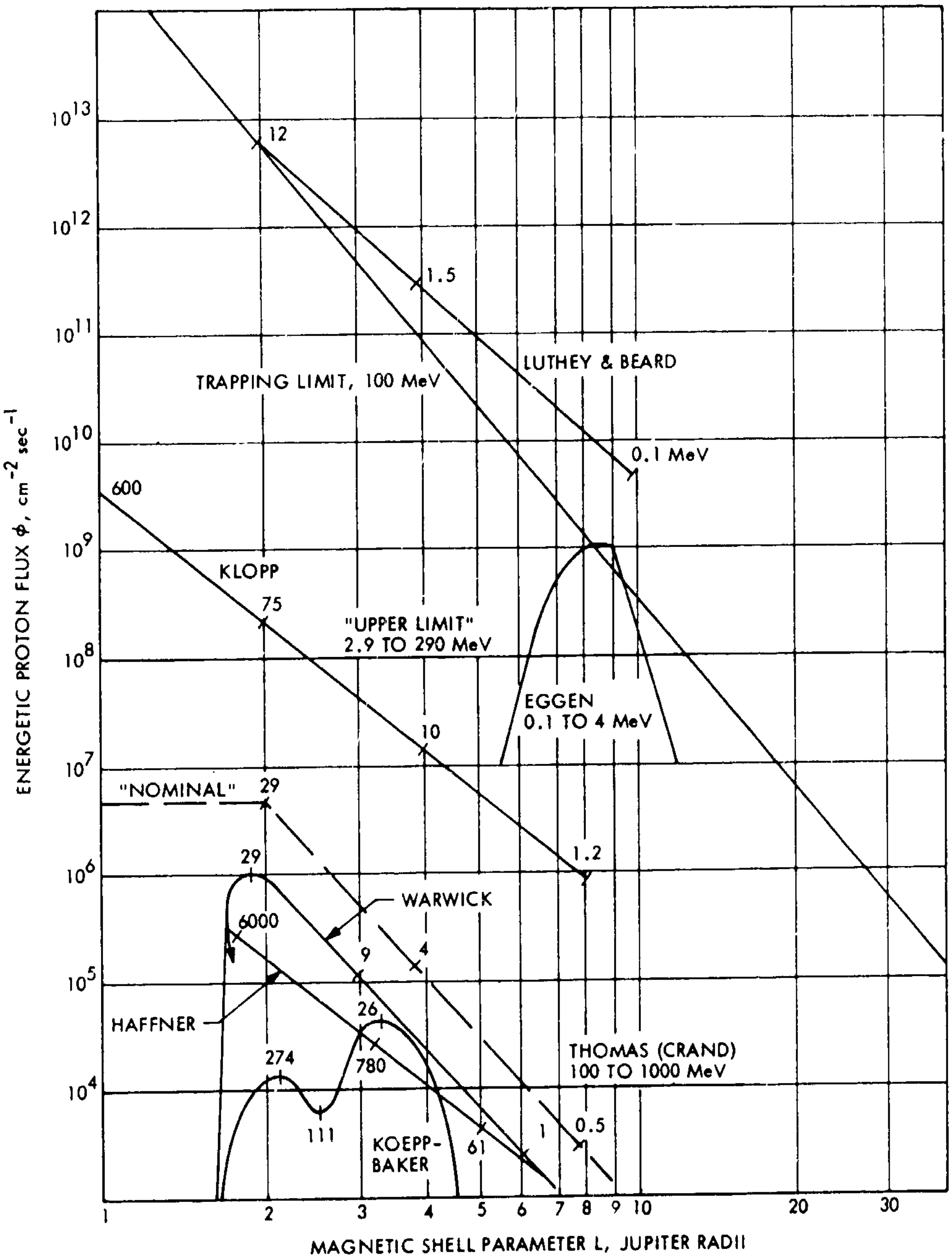

Figure 3. Jupiter Proton Models in Equatorial Plane (energies in MeV)

MONOGRAPH PROTON MODELS

These models are shown in figure 3, and are thoroughly described in references 1 and 2. The nominal model applies Warwick's considerations directly to the nominal electron concentrations. The upper limit model is largely arbitrary, in that it applies uncertainties to the nominal model which are squares of the electron uncertainty factors. Thus, for $L \leq 2$, the concentration and energy are each ten times the nominal values and for $L > 2$ the concentration and energy are proportional to L^0, i.e., independent of distance from Jupiter, until the energy density trapping limit is met.

CONCLUSIONS

The relatively compact set of electron models inspires some confidence in their validity, particularly as they have been derived from numerous data and analysis techniques. Although these models have serious consequences for spacecraft design (refs. 3 and 4), the problems they imply are probably soluble with technologies anticipated for spacecraft to be designed for Jupiter encounter.

By contrast, the proton models are very diverse, fluxes and energies spanning several orders of magnitude even for those models based on physical considerations; this results from the absence of applicable data. However, even in the midrange of these models, the proton energies and fluxes would be severely hazardous to several spacecraft subsystems (refs. 3 and 4). It is therefore desirable to apply further technical consideration to the modeling of Jupiter's energetic proton population.

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DISCUSSION

DR. MEAD: Looking at the top of Figure 3, Haffner has made the comment that inside L=4, the protons do the most damage, and outside the electrons do. If you look at this thing, if you get anything like an approach to the upper-limit model, the conclusions are 1) that it's a heck of a lot worse than the engineering studies we saw, and 2) that it's the protons all the way out we look at and the electrons are small potatoes compared with the protons.

DR. DIVINE: That would be the conclusion. Even the nominal model dropping off as it does here is dangerous for spacecraft which approach within 4, 5, or 6 Jupiter radii. Thus, even the nominal model is not negligible from a damage point of view. That will come out later this afternoon in the other talks.

DR. LIEMOHN: Would it be fair to look, instead of at the flux, at the energy density of a particular model, and then to ask what fraction of the total magnetic energy density are we normally going to have to look to as a workable level?

DR. DIVINE: It would not be difficult to plot the material that way. It would simply skew the entire diagram in a way which makes the trapping limit line horizontal instead of sloping. The information and content would be the same, and it would not be difficult to create such a diagram. For mission analysis and spacecraft design purposes, the flux is the more important consideration.

DR. LIEMOHN: Isn't the combination of the flux and the energy of the particles significant?

DR. DIVINE: Yes. But if you're talking about the energy density relative to that which could be trapped by the magnetic field, that's not the important consideration.

DR. LIEMOHN: I see.

DR. DIVINE: But if you just did it in energy density alone, that would be more appropriate. On the other hand, the damage is not strictly proportional to energy. In fact, the way in which damage scales with energy will be brought out in a later talk this afternoon for the protons.

DR. BEARD: Your point about the bad spatial resolution in our analysis of the electrons is well taken, but the work I will report on tomorrow will analyze some new computer output. It shows that spatial resolution has been taken care of properly. The results are much more reliable, and they're quite a bit different.

The other thing is that I have some qualms in that you refer to our proton estimates and dignify them by the name of a model. It's just an estimate.

DR. DIVINE: It's difficult for anyone to do any better than an estimate at this point.

DR. GULKIS: I think we do have one piece of information on the protons, namely the corresponding thermoplasma, which ties in with Jim Warwick's Faraday rotation model. In fact, these maximum proton fluxes must have a corresponding thermosplasma four orders of magnitude more dense than Jim's measurements allow. If someone who is well acquainted with radio wave propagation could look at the characteristic modes which exist in a magnetosphere, and compare it with Jim's results, then we might be able to decide whether or not that's even a potential model. Some of the work Liemohn has been doing is very pertinent.

DR. WHITE: Could you repeat that again? What is the density of the thermoplasma?

DR. MEAD: I think if there are protons, charge neutrality requires equal densities, and you've got to have that many electrons in the thermoplasma.

DR. BEARD: With that many electrons, don't you mean just the inverse of that?

DR. MEAD: I mean if you take the numbers from Figure 3 and convert the flux of protons to number density, there's got to be an equal number density of electrons. According to Dr. Gulkis, Warwick claims there can't be that many electrons.

DR. WARWICK: At the top of Figure 3, near the numeral 12 at 2 Jupiter radii, I read a flux of about 10^{13} cm^{-2} sec^{-1}, which implies more than 10 cubed per cubic centimeter. That's too large a density for Faraday by orders of magnitude. That's what Dr. Gulkis was saying.

DR. KENNEL: The other suggestion I was going to make is that probably we can rule out the magnetic trapping limit. If the radio observers were really to see a high β plasma, they would see a grossly distorted profile of magnetic field at the Jupiter equator. Such a distortion would look different from what is seen in the decimetric phenomena.

DR. MEAD: I don't believe those distortions of the dipole field could be distinguished from the point of view of the decimetric radiation we have seen. Even if β were to approach unity near L=2, the decimetric radiation would still very likely look the same.

DR. WARWICK: That depends on what the distortion is. I would agree with you if it was an axisymmetric distortion, which is what I think you're implying, and that would be worth thinking about. Nevertheless, the Faraday effect would be enormous with that many particles at that distance from Jupiter.

DR. WHITE: Can I return to the question of the number of thermal electrons here? I will address myself to the upper limit to what one can have in a trapped proton flux on the basis of that model, but that does set a definite upper limit. The number of protons that one has there requires a certain number of electrons for charge neutrality, and because of this density, those protons are going to be lost by ionization. That sets a definite upper limit on what one can have, and it's very close to the horizontal upper-limit model in Figure 3.

DR. WARWICK: You mean 6 orders of magnitude below the number 12?

DR. WHITE: That's right. That's because the trapped protons will be lost by ionization.

DR. BEARD: Your upper limit is set by the fact that you don't observe any Faraday rotation, right?

DR. WARWICK: Right. It limits the total content so that the density depends on the path length. Thus, N times H is of the order of 10 to the 12th per square centimeter, where H is the distance over which there is a certain number of particles per cubic centimeter. What kind of an H are we going to take?

DR. GULKIS: 100,000 kilometers.

DR. WARWICK: Okay. That's 10^{10} cm, which gives you 10^2 per cubic centimeter at L=2. It might actually be a little bit less than that, because 100,000 kilometers is a small distance. That's only 1.5 Jupiter radii, and I'd argue maybe 5 would be better since we're looking across the peak of the belts.

DR. WHITE: Of course, a density that high will lower it even below the upper-limit model in Figure 3 because of the effect on the trapped protons of energy lost.

DR. BEARD: I don't understand that.

DR. WHITE: Well, depending upon the source--one has to have a source for the protons and a loss for the protons, and if one takes a particular model where the loss is by dE/dX, then the equilibrium number of protons goes inversely as the density of the thermo-electrons there. The higher that electron density, of course, the lower the equilibrium level. What I'm saying is that in the model that I'll be talking about tomorrow, that the density of 10 to the 2 per cubic centimeter will reduce that level considerably below the upper-limit model.

DR. THORNE: You have to assume some sort of injection time. What sort of injection time scale do you assume for this calculation?

DR. WHITE: The model uses cosmic ray albedo neutron decay injection and radial diffusion in that it involves loss of particles.

DR. THORNE: Could you get fluxes that high?

DR. WHITE: Yes. It would involve, of course, very long time constants, thousands or tens of thousands of years.

DR. AXFORD: Did you say you can then have a source of electrons without any protons for 10,000 years when you're doing such drastic things?

DR. WHITE: The electron time scale, I would think, would be set by the synchrotron radiation and the proton synchrotron radiation is down by a factor of several million. The time scale for radial diffusion, if one uses the variation of magnetic or electric field, will go as L^{10} or L^6 and these times, when we get in here, are going to be quite high.

DR. THORNE: To get electrons into L=2 is difficult with any diffusion mechanism which depends on some high power of L to get in from the boundary near L=80.

DR. WHITE: If you use Birmingham's numbers for electric field fluctuations, as I recall, at L=3, it's something like 30 years.

DR. KENNEL: And the point is, the radiative lifetime is like a year. The fact is that there's a discrepancy. So, presumably, if it's radial diffusion, the radial diffusion is faster than Birmingham's.

DR. WHITE: As I said, it depends on the energy of the electrons you're talking about, too. One can balance these two at L=2.81, for example, if you use electrons at 5 MeV at about L=2.

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PREVIOUS DESIGN RESTRAINTS AND RADIATION DAMAGE EFFECTS OF LOW ENERGY PARTICLES

James H. Trainor*

INTRODUCTION

There are two purposes for presenting this paper. Mr. Beck requested that I restate the position held by the GSFC study group in the period 1967-1969 concerning Jovian radiation belts and the radiation design limits for spacecraft flying by Jupiter. Secondly, I'd like to remind people of the damage effects due to potentially large fluxes of low energy protons and electrons in the Jovian magnetosphere. It has been my experience that the high energy protons (>20 MeV) and electrons (>1 MeV) attract most of the interest, concern and attention. While this attention is proper, one cannot neglect the lower energy particles and their effects. It has been perhaps two years, since I have listened to or read of such a discussion.

PREVIOUS DESIGN RESTRAINTS

Figure 1 summarizes the design fluences for Jovian electrons and protons resulting from the Outer Planets Explorer (OPE) studies at the Goddard Space Flight Center in the Period 1967-1969. The principal references which one could cite at that time were the papers by Chang and Davis (1962), Warwick (1967) and Eggen (1967). The data will be generally presented as a fluence or time integrated flux of particles of energy greater than a stated value.

Jovian Electrons - For electrons with energies greater than 5 MeV, the spacecraft design fluence was 10^{11} electrons/cm^2. This fluence is close to the present nominal model presented earlier by Dr. Divine. At energies below 5 MeV, the integral spectrum was assumed to go as E^{-2} as sort of a

*Laboratory for High Energy Astrophysics, Goddard Space Flight Center, Greenbelt, Maryland 20771.

worst case. Note the comment at the bottom of Figure 1. We were uncertain of these numbers, so we required the hardware designers to consider and comment upon the effects of much larger fluences.

Jovian Protons - I chose the design fluences shown in Figure 1 for protons based primarily upon system damage thresholds and not based upon any model of Jupiter's magnetosphere. Protons with energies greater than 30 MeV will penetrate into the electronic assemblies within the spacecraft, and damage effects in silicon semiconductor devices begin at about 10^9 protons/cm^2. Similarly, the effects of low energy protons on exposed systems begin at about 5×10^{14} protons/cm^2, as will be discussed later in this paper. Designers were cautioned that fluences could be several orders of magnitude larger or smaller than the values quoted. The need for data from an early Pioneer F flyby of Jupiter was apparent.

Radioisotope Thermoelectric Generators (RTG's) - From the beginning, it has been apparent that one has to be very careful in the manner in which the RTG's are integrated into the spacecraft system. The primary emission from RTG's are neutrons and gamma rays with energies up to a few MeV. The most sensitive items on the spacecraft were determined to be the sensors in the various possible particle experiments. The gamma ray fluxes shown in Figure 2 (as a function of energy) were based upon real time interference with the measurement of cosmic ray electrons. The neutron fluxes, however, were based upon integrated damage effects in silicon solid state detectors. The primary effect is a reduction in charge-collection efficiency. The mission fluence was calculated at 3×10^9 neutrons/cm^2, representing the maximum allowable degradation in detector operations. Our best present estimate for the allowable neutron fluence at the location of the silicon solid state detector varies between 10^9 and 10^{10}neutrons cm^{-2}, ($E_n \geq 10$ KeV) depending on the type of diodes used and how they were manufactured.

RADIATION DAMAGE EFFECT OF LOW ENERGY PARTICLES

While the possible fluxes and resultant damage effects of high-energy particles in the Jovian magnetosphere get a large amount of attention, one should not overlook the effects of low-energy electrons and protons on

ELECTRONS

10^{11} Electrons/cm^2	E > 5 MeV
Integral Spectrum as E^{-2}	E < 5 MeV

PROTONS

1.5×10^9 p/cm^2	E > 30 MeV
5×10^{14} p/cm^2	E > 100 keV

GREAT UNCERTAINTY

DESIGNERS SHOULD
CONSIDER AND COMMENT ON
THE EFFECT OF HIGHER FLUXES

Figure 1. OPE/GSFC Jovian Design Fluences (1967-69)

PARTICLE

EXPERIMENT

LOCATIONS

ENERGY REGION	GAMMA FLUX	NEUTRON FLUX
MeV	γ/cm^2 sec	n/cm^2 sec
>0.5	2.5	12.5
>1	1	5
>3	0.25	1.25

8-YEAR NEUTRON FLUENCE ~ 3×10^9 n/cm^2

Figure 2. OPE/GSFC Radioisotope Thermoelectric Generator Radiation Constraints (1967-69)

exposed systems. Here, low energy means electrons with energies less than ~0.5 MeV and protons with energies less than ~10 MeV. These particles cannot penetrate the usual spacecraft outer walls. Therefore, the primary concern is with thermal surfaces, reflective surfaces, refractive materials and various science detector systems. I will go through each topic briefly, and the references contain much more specific material.

Figure 3 summarizes the effects on spacecraft thermal surfaces. The absorptivity and emissivity do change significantly. Effects have been noted for electrons with energies greater than 5 to 10 KeV, while the effects seem to be maximized for protons with energies ~100 KeV. The effects begin to be significant at fluences of $\sim 10^{15}$ particles per cm^2, and the changes are large at $\sim 10^{16}$ particles per cm^2. If one reviews the available data, it's apparent that much of the data is inconsistent and this is attributed to surface contamination prior to and/or during irradiation.

Figure 4 is a similar summary for reflective surfaces. There used to be considerable scatter and inconsistency in the data for irradiated reflective surfaces also, but much of this scatter has now been removed. Investigation has shown that in the process of irradiation in vacuum chambers, the surfaces became contaminated with vacuum pump oils and the post irradiation by products of such oils. Subsequent irradiation in Vacion-pumped chambers lead to consistent data. Metallic, metallic oxide and inorganic oxide surfaces appear to have stable reflective properties to at least 10^{16} protons/cm^2 for E_p ~10 KeV. The need to keep contaminants away from the spacecraft both in the ground testing and in flight is apparent.

The problems with refractive materials are summarized in Figure 5. The darkening of optical elements due to the creation of color centers is well known. Light generated in the refractive materials by fluorescence and Cerenkov mechanisms is a real time interference problem in the design of an experiment, especially for those experiments to function inside the Jovian magnetosphere. In the energy ranges of concern here, protons appear to be far more damaging, and one could conceivably accumulate from 10^{14} to 10^{18} protons cm^{-2} with energies greater than 10 KeV. Such fluences could be very damaging,

THERMAL SURFACES: ABSORPTIVITY AND EMISSIVITY

EFFECTS BEGIN $\sim 10^{15}$ PARTICLES/cm^2

FOR ELECTRONS OR PROTONS

LARGE CHANGES $\sim 10^{16}$ PARTICLES/cm^2

$E > 5$-10 KEV ADEQUATE

$E \sim 100$ KEV WORST

CONTAMINANTS?

Figure 3. Radiation Effects on Thermal Surfaces

REFLECTIVE SURFACES

REFLECTIVITY:

900 - 6000 Å —

VARIOUS SUBSTRATES COATED WITH ALUMINUM & RECOATED WITH MgF_2

*RESULTS

IN ABSENCE OF CONTAMINANTS, THERE WERE NO EFFECTS FOR 10^{16} p/cm^2, E_p = 10 keV.

Large effects due to slight contaminants in vacuum.

Figure 4. Radiation Effects on Reflective Surfaces

REFRACTIVE MATERIALS*

CREATION OF COLOR CENTERS — FOR EXAMPLE, DAMAGE EFFECTS BEGIN AT 10^{12}-10^{13} p/cm^2, FOR PROTONS OF 10 MeV ENERGY.

MOST DAMAGE NEAR END OF TRACK.

ELECTRONS ARE NOT A DAMAGE PROBLEM UNTIL ~10^{15} e/cm^2.

PRESENCE OR ABSENCE OF IMPURITIES IS CRUCIAL

FLUORESCENCE AND CERENKOV RADIATION CAN BE PROBLEMS.

*Most refractive elements should not be exposed to direct low energy particles.

Figure 5. Radiation Effects on Refractive Materials

leading to my comment at the bottom of Figure 5, that one should be very careful about using refractive elements within experiments or spacecraft systems on Jovian missions.

Some materials, such as sapphire, are more tolerant of radiation with respect to the creation of color centers, but the effects due to Cerenkov radiation will be more pronounced due to the higher index of refraction of sapphire. If the higher end of the Jovian radiation models apply, not even sapphire will help you. Considering the uncertainties involved in the Jovian radiation models, it would seem wise to design optical systems using reflective optics.

Figure 6 summarizes my closing remarks. Jupiter is a major point of interest on all of the outer planet missions, and most of the science detector systems will be required to function in the Jovian radiation belts. Such radiation belts may exist at other outer planets also. The potential high energy particles in Jupiter's radiation belts have received wide publicity, and most experiments have tried to account for the possible effects. For the most part, only the energetic particle experiments have hard data concerning radiation effects upon the detectors and the frontend electronics. Most experimenters have not concerned themselves as yet with the potential effect of large fluences of low energy particles, especially protons. The effects can be very tricky. While the transconductance and current parameters of field effect transistors are stable for the predicted fluences, the high frequency noise figure may increase markedly. Another effect is the buildup of charge on insulating surfaces, resulting in large electric fields. It is difficult if not impossible to predict analytically all of these effects. One has to test the systems in such an environment.

In the selection procedures for participation in the SSG activities, a radiation effects analysis was not required. Later this year, a design model of Jupiter's radiation belts will be available. Using this model, a radiation effects analysis should be a part of each experiment proposal. The analysis should include low energy particles also, for those experiments with exposed detector systems, as well as the effects of the RTG or RHU neutrons and gamma rays.

SCIENCE DETECTOR SYSTEMS:

(1) MOST EXPOSED SCIENCE DETECTOR SYSTEMS ARE REQUIRED TO FUNCTION IN THE JOVIAN RADIATION BELTS.

(2) OTHER THAN SOME PARTICLE EXPERIMENTS, I AM AWARE ONLY OF GENERAL COMMENTS CONCERNING OTHER EXPERIMENTS' ABILITY TO FUNCTION IN THE PROPOSED NOMINAL FLUXES. CHRONIC EFFECTS IMPORTANT, ALSO.

(3) I DON'T BELIEVE THAT MOST EXPERIMENT DESIGN HAS CONSIDERED THE POTENTIAL EFFECTS OF LARGE FLUENCES OF LOW ENERGY PARTICLES.

(4) THESE WOULD BE APPROPRIATE TOPICS (*see text*) TO PRESENT TO THE SCIENCE STEERING GROUP IN THE FALL.

(5) RADIATION EFFECTS ANALYSIS SHOULD BE A REQUIRED PART OF EACH EXPERIMENT PROPOSAL.

Figure 6. Comments on Science Detector Systems

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DISCUSSION

MR. BECK: What can you say, in general, about the operation of science instruments? How large can the flux be before you really have a problem?

DR. TRAINOR: It's almost a unique function of each type of system. We understand solid-state detectors very well. There is at least an order of magnitude difference in tolerance to the damage effects depending on which manufacturer's detectors are used, their type, and how large an electric field can be applied. If one compares solid-state detector systems with Faraday cup systems or television systems, the numbers are quite different and are dependent upon the exact system one chooses. Dick Parker will show numbers for various science systems which vary widely. In general, the tolerable fluxes and fluences are smaller than the design fluences that the JPL study is advertising as mandatory.

DR. BEARD: I suppose it would be impossible, but how difficult would it be to get a super-conducting magnet or even a magnet that one could turn on when entering Jupiter's environment in order to protect against fluences of low-energy particles?

DR. TRAINOR: It would be interesting to see what the spacecraft would do in the Jovian magnetic field in terms of altitude control. This would also rule out the magnet. The pointing accuracy required on this spacecraft going by Jupiter is rather high.

DR. LIEMOHN: Once again, is the problem a matter of flux, energy, or is flux alone the key?

DR. TRAINOR: Neither is the right answer, I think. Displacement damage is the primary mechanism that one usually worries about in crystalline materials such as the silicon in most transistors. If you are talking about metal oxide silicon transistors, you worry primarily about ionization. There is a different mechanism of damage going on there. In most instances in the JPL study and also in the Goddard work, you will see something like a fluence of particles with an equivalent energy as a stated way of presenting the result. We know from working with radiation damage effects on solid-state detectors that that's the only way that really makes sense. If you look at very low-energy particles on solid-state detectors, you can tolerate 10^{18} protons/cm^2 of a few hundred keV, for instance, but this does not scale with energy deposited in the detector. If you look at a few MeV (a factor of ten in energy difference), the tolerable fluence is a factor of 10^4 lower.

MR. PARKER: In addition to that, it's the different types of detectors that you really have to worry about and too, where this energy is deposited.

DR. TRAINOR: Yes. Damage effects as seen through the ohmic contact on surface-barrier detectors are much less than for the effects seen through the junction contact for protons of a few hundred keV. Once the proton energies get up to a few MeV, and begin to penetrate the detector fully, then it doesn't matter much which way the protons entered.

MR. THOMAS: What periapsis did your mission use for the Jovian design fluence?

DR. TRAINOR: At that time, I think it was about $3R_J$. Directly scaling fluences from $3R_J$ would be troublesome because we had a considerably lighter spacecraft than is being talked about here; and as a result, we had a shorter flight time (about eight years). Thus, we would go through the belts faster, and of course, fluence is a function of time and so on.

MR. THOMAS: Still, the speed at $3R_J$ is mostly due to the kinetic energy acquired at Jupiter.

DR. TRAINOR: Yes, it is; but I was thinking of the low-energy particles also, and therefore, the total time spent inside $40R_J$. For a fluence of 10^{11} electrons/cm^2 of higher energy electrons, your comment is right.

DR. HAFFNER: In connection with your work, did you look at now only permanent damage but temporary noise, for instance, in electron multipliers? I suspect that there, it would be even more severe.

DR. TRAINOR: I gave a paper this morning to Dick Parker that comments exactly on that. Many of the instruments that people are proposing for use at Jupiter (photometers, for instance) are subject to real time interference as well as chronic damage. Dr. Hunten commented here at a recent Science Advisory Group meeting that most photometers malfunction in Earth orbit while passing through the South Atlantic anomaly at 1000 km. The radiation there is made up primarily of electrons ($E_\beta \sim$ 100 keV to $\sim$1 MeV) with fluxes of $\sim 10^3$ cm^{-2}sec^{-1}.

DERIVATION OF MISSION FLUENCES FROM FLUX MODELS: PROPAGATION OF UNCERTAINTIES*

Jack Barengoltz**

I would like to address two subjects today. I'd like to address the topic of how to calculate fluences from the flux models or, in other words, what the spacecraft designers finally need from flux models. In particular, I would like to say something about what some of the uncertainties in the flux models do to lead to even larger uncertainties in the final answer that you get when you worry about what you have to design to or, in a nonstandard definition, the propagation of errors.

First of all, Figures 1 through 5 are going to be used for both of those purposes. I will possibly say a word or two about what counts: fluence, dose, energy, or a combination, and essentially go into what Dr. Trainor mentioned, a fluence of an equivalent energy. I will now say a few words about our version of equivalent fluence.

Figure 1 is a graph for electrons on silicon of dE/dx on the left-hand axis and range on the right-hand axis versus energy. dE/dx is one way to weight flux. In fact, dose is a collapsed spectrum using dE/dx as a weighting function. This is important if ionization is important for the device under consideration, and the answer comes out in rads.

Ionization is the removal of electrons from the atoms of the material of the device under consideration. This is ordinarily a temporary effect, because everything likes to get back to charge neutrality. In the case of a science detector, you see a pulse. A sufficient number of electrons were knocked off to produce that pulse. In the case of an MOS device, the structure

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**Jet Propulsion Laboratory, Pasadena, California 91103.

of the device is such as to trap the charge on a fair time scale, and you can get a "permanent" effect for purposes of circuit design, rather than a temporary effect. That is only half of the story, because you also have to consider displacement.

Figure 1 also contains a range curve because the other half of this talk is to make a plea for what parts of the uncertainties or models seem most important to me at this point. For other things besides a science detector, you always have a little shielding to help out, and the minimum we have been using here is what was quoted as a minimum spacecraft electronics box wall thickness, 50 mils of aluminum or 0.343 g/cm^2. As indicated on Figure 1, that's about the range of a 0.7 MeV electron. For first approximation, I only worry about electrons having energies greater than 0.7 MeV.

The other thing you can notice is that dE/dx is not a strong function of the energy. Assume that ionization is important, and the spectrum is peaked about some energy. Then if you work very hard to tell me exactly what the characteristic energy of that spectrum is, it won't help me as much as some other quantities in the models that you might tell me about more accurately.

In Figure 2, I have the other half of electron-induced damage, which is, in some sense, the displacement damage relative to a certain energy. Now, there isn't any absolute way to measure displacement damage, except to get in there and count the defects. Even that doesn't work, because, as it has been said, the damage doesn't scale with energy, the reason being that the type of defects that form change with the energy of the bombarding particle. A simple defect anneals more easily than a very complicated defect. You get clusters of defects from a very energetic particle, and the cluster will tend to stick around and cause more trouble than an equal number of simple defects spread out through a device.

Generally, you see that, in a relative sense, on an arbitrary scale, the displacement damage from electrons also goes up with energy. It is also a good deal steeper than the ionization. The way these numbers were found is: for different types of devices that are sensitive to displacement damage,

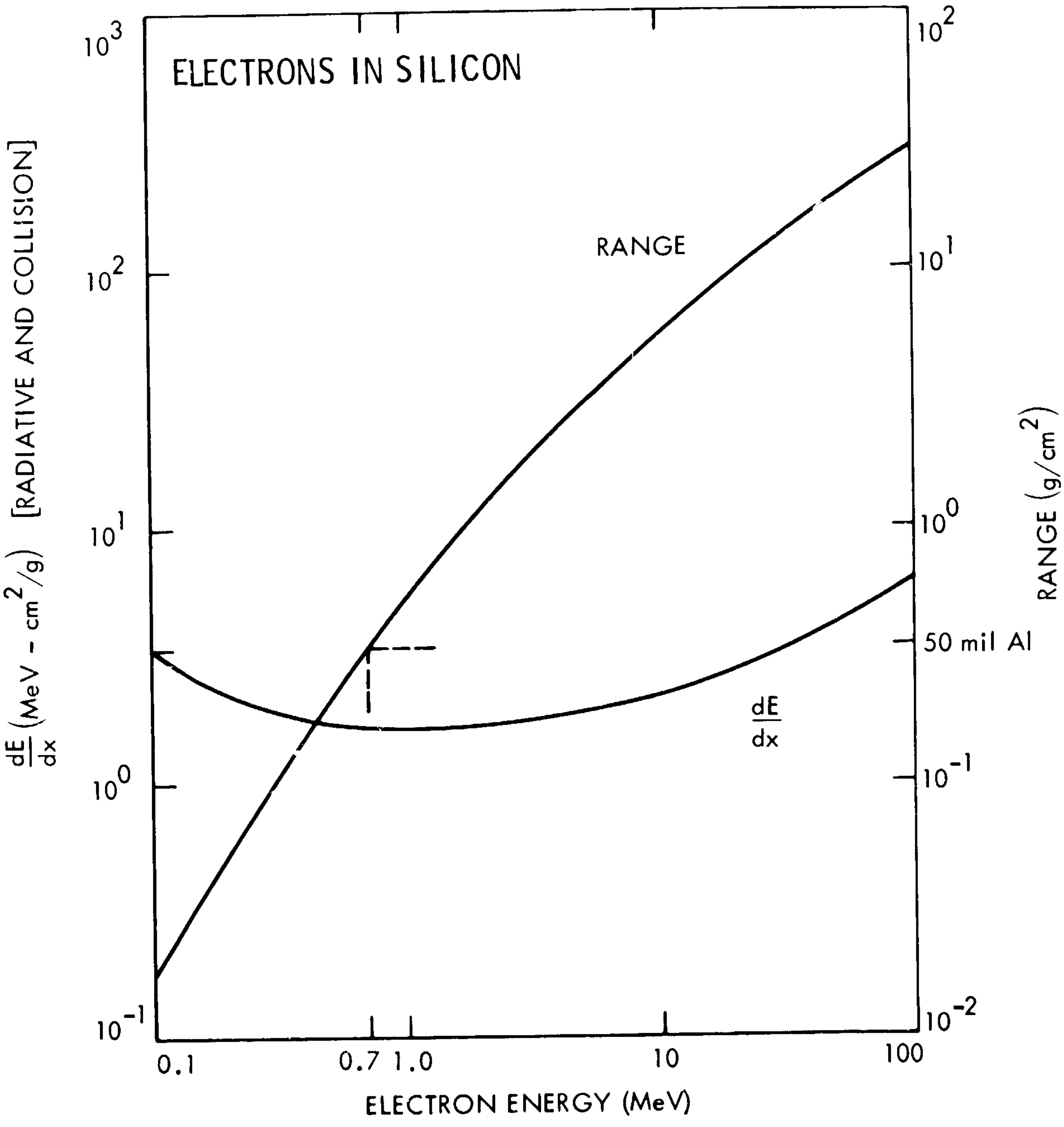

Figure 1. Stopping Power and Range Curves for Electrons in Silicon

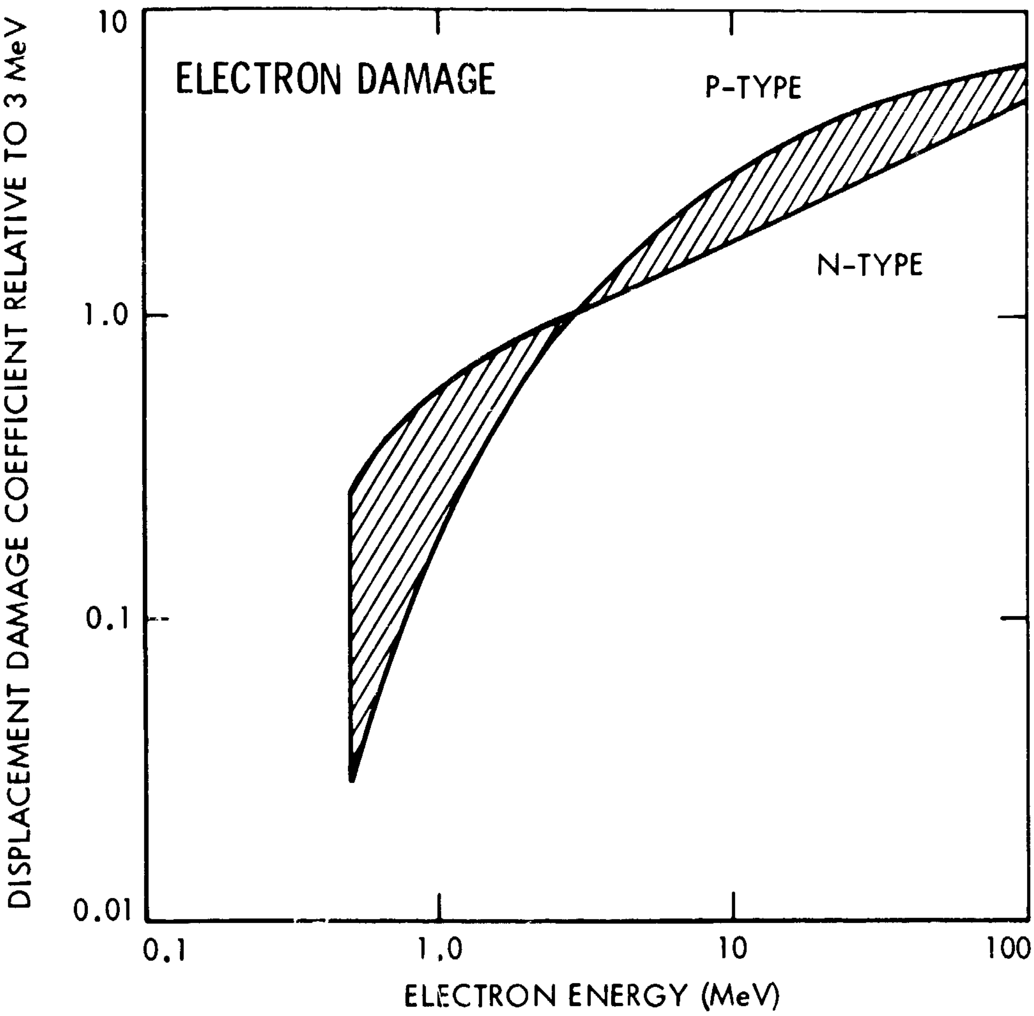

Figure 2. Relative Electron Displacement Damage in Silicon

the relative value of some characteristic parameter as a function of bombarding energy at the same fluence of electrons was obtained. It is fairly qualitative, and it is based entirely on experimental data and not on theoretical data.

Displacement damage is defined for a crystalline material, as the removal of atoms from their lattice position, so it is an entirely different effect from ionization. Its energy dependence is entirely different. In fact, there is an energy threshold for this effect that is higher than for ionization.

Once again, though, within the energy ranges that the characteristic energy of a spectrum might vary within the models and the uncertainty of this quantity, a change in the characteristic energy of the spectrum would not have a great effect, unless you came up with a characteristic energy that was so low that for everything except a science instrument, say, the electrons wouldn't get through a spacecraft wall. Then, considering this, there would be no further worry about electrons on electronics, but only problems with the science instrument. Other than that, exactly what the energy spectrum is, does not seem the most important consideration for model improvement--at least if the interest is to improve the uncertainty of the models for the purposes of spacecraft design.

Figures 3 and 4 are for protons on silicon. Figure 3 shows the ionization in silicon due to protons. One of the things that you have to remember here in the other half of this talk about how to go about calculating fluences is that for the electrons, both the displacement damage and the ionization went up with energy. When given a model that has an uncertainty in energy, I just take the largest energies that the model allows and call that the worst case. In the case of protons, it is sort of nasty. The ionization damage goes down with energy, but it isn't correct to say, "We will just take the lowest energy allowed by the model." As previous speakers have mentioned, you have the question of whether the proton penetrates to the area where you don't want the proton to cause its damage and deposits its energy. So you have a trade-off, and then you have recourse to the range curve again. If I invoke the 50 mils of aluminum once more, then I find that 50 mils of aluminum is

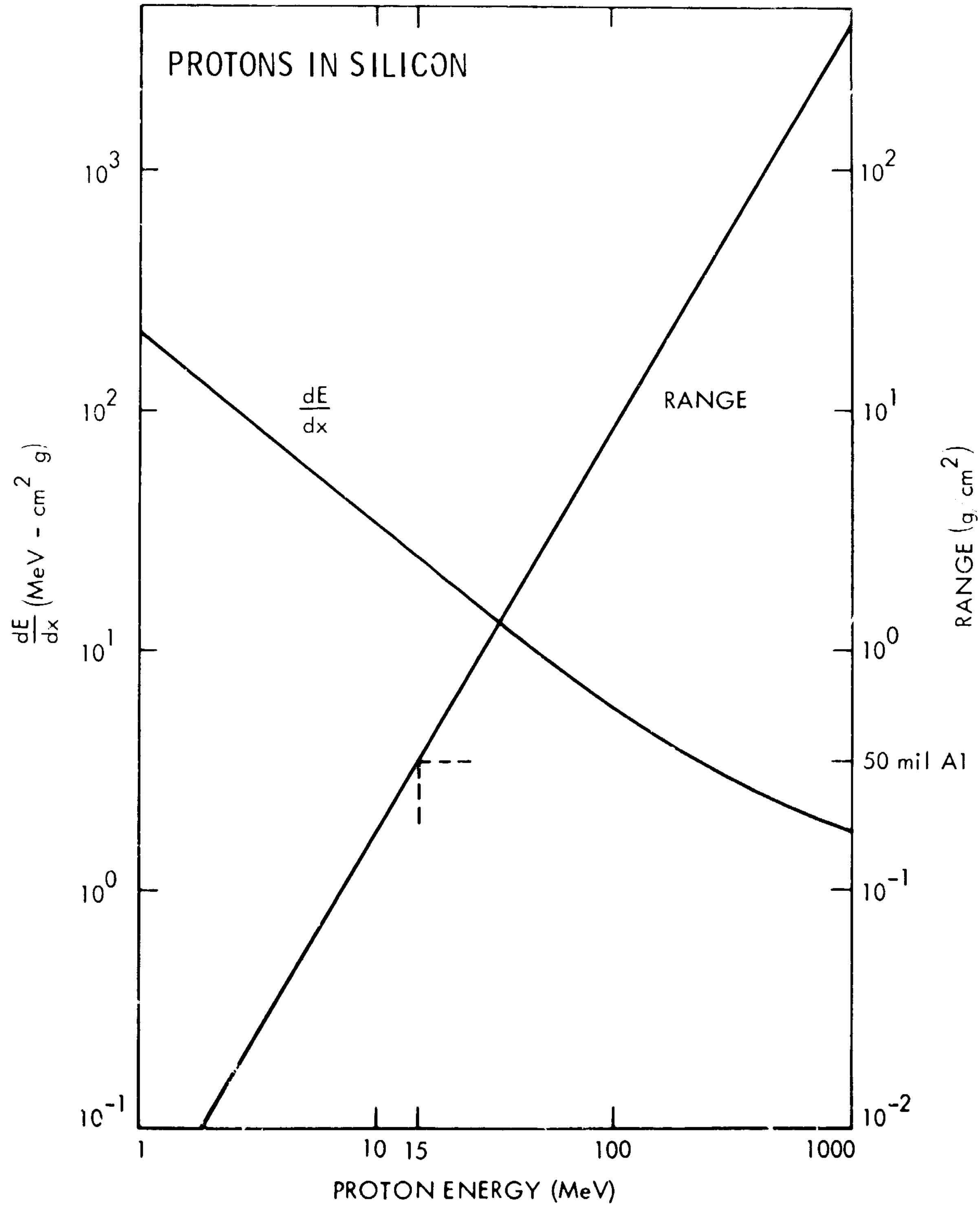

Figure 3. Stopping Power and Range Curves for Protons in Silicon

about the range of a 15 MeV proton. For the most part, I am not too interested in protons with lower energies, except for science instruments that are exposed.

dE/dx is somewhat steeper than it is for electrons, but still, within the range of the uncertainties of Divine's spectrum which is between 2.9 MeV and 300 MeV, there are worse problems or there are other uncertainties that cause larger divergencies in the answers, as we will see in a minute. The 2.9 MeV characteristic energy would be very nice, because it gets down where almost any amount of shielding will do a very good job, even a transistor can. If someone could certify that spectrum or a similar spectrum with a small characteristic energy or one with a $\frac{1}{E}$ energy dependence, I uld be very pleased.

Before continuing, we must also consider the energy dependence of proton-induced displacement damage (Figure 4). We have the fortunate case of displacement damage also going down with proton energy, as well as dE/dx, so that trade-off I mentioned before is all right. Otherwise, it would be difficult from device to device to even say whether you would prefer higher or lower energy protons, given your choice. Nature wasn't quite so perverse, and the displacement damage goes down with energy. Now, I must add that this is only true for devices that are thin to the range of the proton energy, but at energies up like this--a hundred MeV--it would take a very thick device not to be thick in that sense. That is, obviously, the higher energy proton (in its range) will cause many more total displacements than the lower energy proton. However, the relative damage shown in Figure 4 is, in effect, a measure of the density of displacements that are formed. When the device is thin as compared to the range of proton, the proton loses very little energy in forming displacements in the device when it is still moving along fast. As it slows down, it gets worse, and if you had a thick device, parts of the device would see this greater effect. As it got towards the end of the range, one would have to consider the actual energy of the proton if it were still in the device.

Now, from Figures 1 through 4, we have a means at hand to essentially create a damage-equivalent fluence. That is, for either electrons

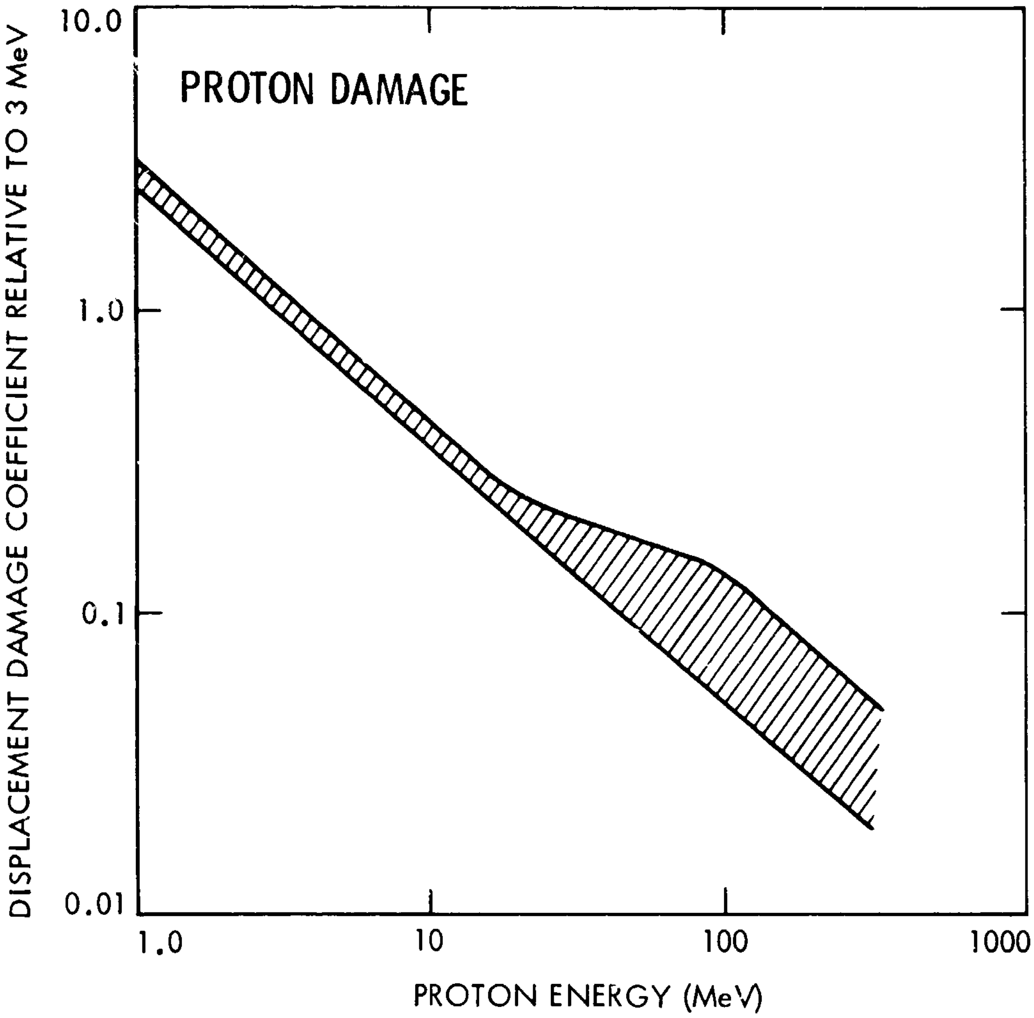

Figure 4. Relative Proton Displacement Damage in Silicon

or protons, one could conservatively choose a function D of the energy, which is a weight proportional in some sense to the damage caused by that particle of that energy. The models provide a spectrum as a function of distance, and also, the flux as a function of position. Of course, the trajectory is the position as a function of time. One can multiply these three quantities together and integrate to get one number, which is the fluence seen by a mission in terms of some reference energy of that particle. The intent of that, among other things, is to be able to estimate what the sensitivity of different parts of the spacecraft are to that environment. Knowing the damage in some sense (as a function of energy) also enables you to compare or estimate these results given experimental data, which are usually done at different energies than the one that you have chosen. Finally, it gives you a chance to test something, because you can then irradiate some component to that fluence of that particle at that energy.

There is an uncertainty in the models that has been talked about at great length. It is the obvious one, the peak flux--the overall normalization of the model. I am not going to say too much about that because the answer I'm going to get is approximately linear (in the peak flux) within the range of reasonable radial dependence and reasonable trajectories. If someone could cut the flux down by a couple of orders of magnitude and be sure about it, that would be very good, obviously.

I am going to get on to something that is important, that right now seems to be a large uncertainty in the flux model that leads to even larger uncertainties in the fluences for particular trajectories, and that is the spatial distribution of the flux. Possibly the easiest way would be to show Figure 5, which shows mission fluences in the electron flux model. This shows the fluences for electrons as advertised. These are 3-MeV equivalent electrons. The upper curves are based on the upper-limit engineering model by Divine. Both the L dependence of the energy and the L dependence of the flux are for the upper limit engineering model. These are shown for flybys in the equatorial plane. These are also shown for two different deflection angles of the trajectory. The ordinate is the periapsis, and those two parameters are sufficient to get the answer out.

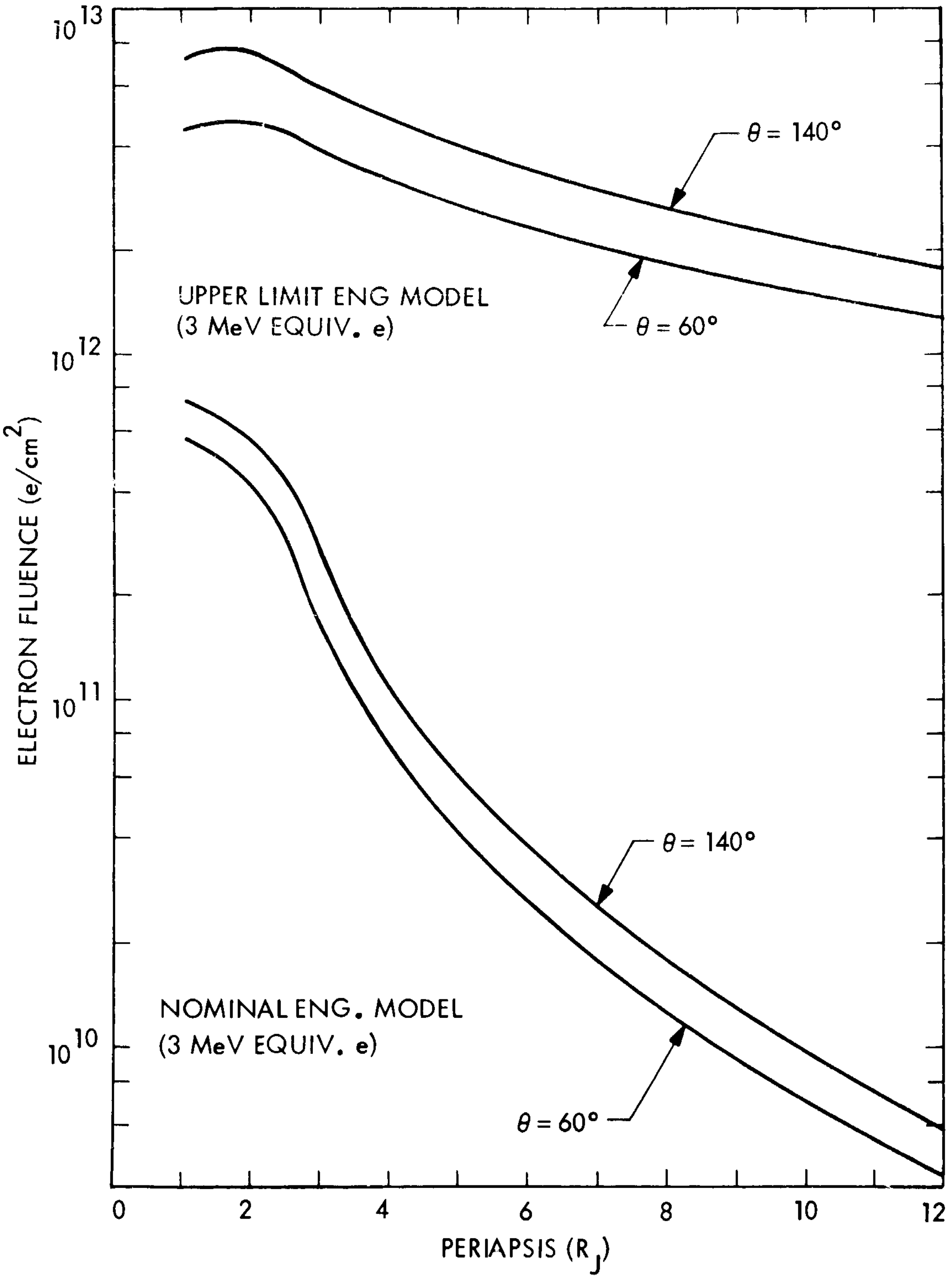

Figure 5. Electron Fluences, Expressed as 3 MeV Equivalent, for Flyby's in the Magnetic Equatorial Plane of Jupiter (θ is the deflection angle of the trajectory)

Looking at a periapsis of 2, you can see the appr(imate order-of-magnitude uncertainty in the electron model for the peak flux between the upper limit and the nominal model. That's fine, because that's what it is supposed to be. What I want to point out is what happens if you go out a few periapses divisions. You see that the nominal model reduces rapidly compared to the upper limit. Now these values have already been integrated so that if you choose to fly a mission of periapsis of about 6, and you have to go with the upper-limit model, you have to pay a serious penalty because of all this uncertainty.

This situation results from the fact that the nominal model has an L^{-4} dependence, which has been mentioned several times today for the diffusion model. The upper-limit model sort of takes a conservative approach and changes that to L^{-2}. A little change in that dependence goes a long way. You can go from one order of magnitude easily, for the missions that have been looked at--out to 3 or 4 orders of magnitude. What I'm trying to do is make an impassioned plea to settle the radial dependence. Alternatively, an outer-radial cutoff would be helpful. I will also settle for an energy dependence which for sufficiently large L, reduces the electrons' energy below that required to get through a reasonable amount of inherent shielding which would, in effect, be an outer-radial cutoff. All of these things would bring that upper limit (or what we are designing to) down a great deal.

Now to get on to the "worst" of all, Figure 6, which shows the same graphs for protons. These fluences' equivalency is 20 MeV, which seemed useful for test purposes. That is, you have to have a fair proton energy to penetrate the containment of what people will want to test. Of course, if you knew the dependence of the damage on energy, you could change these around to any other energy. It would just be a scale factor.

For protons, we really suffer because, as you recall from Divine's presentation, the upper-limit proton flux model had no radial dependence at all out to about 16 R_J, where it started going down as L^{-6} along the

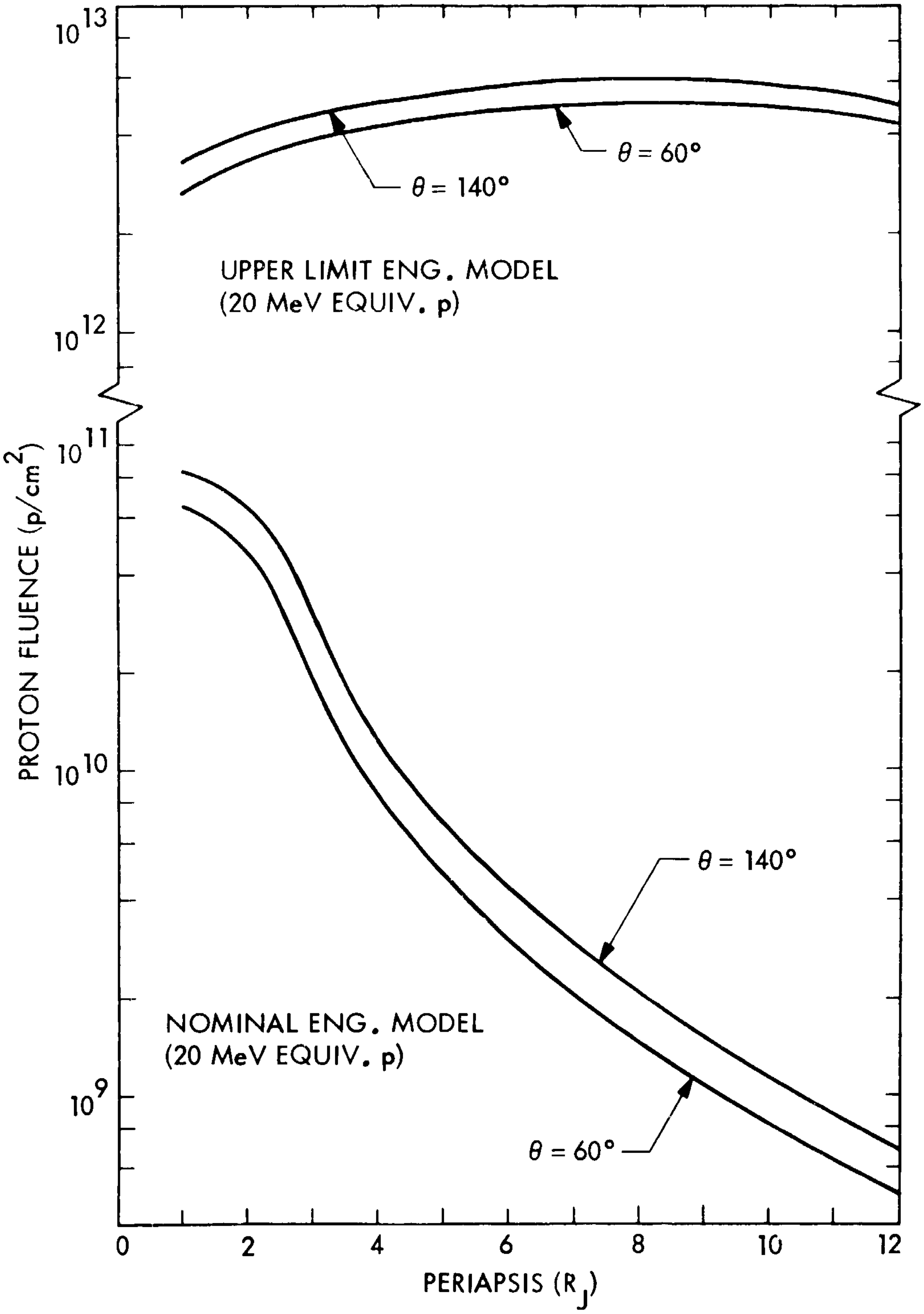

Figure 6. Proton Fluences, Expressed as 20 MeV Equivalent, for Flyby's in the Magnetic Equatorial Plane of Jupiter (θ is the deflection angle of the trajectory)

magnetic trapping limit. The effect of this is the perverse problem that when you fly farther out, you may receive even more fluence than when flying closer. This is because there are protons everywhere in essentially equal numbers. Thus, it is a matter of how long you're around Jupiter rather than how close you fly to the planet.

In the case of the protons, if we fly out from the planet at all, one would really like to know for certain that L^{-4} was the radial dependence of the flux rather than that flat dependence, because things really, really get bad. Of course, I don't even want to talk about the magnetic trapping limit.

In summar[illegible] am faced with calculating the fluences with uncertainty in the peak flux, uncertainty in the energy spectrum, both in the shape and energy location of the peak, if any, and uncertainty in the spatial distribution of the flux. To reiterate, the ranking I apply to those is first the uncertainty in the peak flux. That has an immediate linear effect. The uncertainty in the spatial distribution, unless I fly near the peak, gives me great divergence between the upper-limit model and the nominal model; and in the case of protons, actually precludes, if the upper-limit model is applied, any mission planning in order to make the situation better. Finally, I do not attach a great deal of importance for mission planning to the energy spectrum, unless it is in the detailed dependence with position (so that the energy would rapidly get below what is considered important to a spacecraft. If the spectrum is fairly constant with position and is of reasonable energy--reasonable energy being above 15 MeV for protons and above 0.75 MeV for electrons--I don't care as much what its dependences are.

DISCUSSION

MR. BECK: Which one of these sets of damage curves do you use to collapse an energy spectrum?

DR. BARENGOLTZ: Well, as I said, one basically takes a conservative approach, which is to say, given what the flux model says, you know which curve (displacement or ionization) will lead to a larger value of equivalence--the equivalent fluence. In these cases, it turned out to be the displacement damage, at the reference energies we were using. If you took some reference energy that was way out and not anywhere near the range that the model predicted the particles to be, you could have changed that to the other case, but the nominal proton model is 29 MeV and the nominal electron model is 6 MeV. For particles of that kind of energy, if you want to collapse a spectrum, the displacement damage curve always leads to bigger numbers.

DR. TRAINOR: First off, could we have that last view graph (Figure 6) shown? To put it in prospective a little bit better, perhaps, if you believe in nominal model rather than the worst case, things might not be all that bad in that a '77 Grand Tour flyby has a periapsis of something like 5 or 6 R_J and for the '79 JUN missions, it is more like 8 or 9. So, you're down in the range of 10^9 (p/cm^2). That is a livable situation.

DR. BARENGOLTZ: I don't argue. I, unfortunately, have been constrained not to talk about that, because another speaker is going to get to that. I would love to go with the nominal model.

DR. TRAINOR: The high model, on the other hand, is totally unlivable.

DR. BARENGOLTZ: Right. Therefore, I need you gentlemen to give me a good excuse to go with the nominal model. Note that if the flux dependence of the upper-limit model had to be used, then suddenly my interest in the energy spectrum would increase immensely, because as soon as you're going to try to shield, then that's crucial. With the characteristic energy, the Divine model allows a nominal of 29 MeV, that is, most of the protons are around 29 MeV, but it will allow them to be around 290 MeV. Well, the answer, then is quite difficult because you can't really shield too well against 290 MeV protons on a spacecraft.

DR. MEAD: I'd like to clarify to see if I understood what you said properly. You said that if you are limited to protons less than around 15 MeV, which is about what you say normally would be stopped in a typical aluminum thickness of 50 mils. Then you can have quite high fluences of less than 15 MeV, and at least the electronics which are inside these aluminum boxes will probably not be affected.

DR. BARENGOLTZ: That's true.

DR. MEAD: But that, of course, does not bear on some things that Jim Trainor said, having to do with other aspects of the mission.

DR. BARENGOLTZ: Well, it neglects the exposed science detectors like scintillation crystals and solid-state detectors.

Someone ended a talk one time here, after talking about damage to transistors and so on, by saying that electron tubes are inherently very radiation hardened. There is an equivalent for science, and that is Faraday cups and ionization chambers. There are some science detectors that can survive fields this high. Then there's another separate problem of interference, about which someone already asked, and which will be addressed by the next speaker.

MR. BECK: Could you make some general comments about fluences for orbiters?

DR. BARENGOLTZ: An orbiter in a magnetic equatorial plane with an apoapsis which is fairly large compared to its periapsis accumulates a fluence per orbit which is approximately the same as that for a flyby with the same periapsis. An orbiter, however, receives this fluence during every orbit. A second consideration is that orbits are not constrained to the equatorial plane. Flybys out of the magnetic equatorial plane cannot encounter the succeeding outer planets in the multi-planet missions very easily. Orbiters with a polar orbit receive a 1 to 2, or even 3 orders-of-magnitude reduction in the fluence, depending on the periapsis. If you put the periapsis over the poles, you do better than if you put the periapsis in the equatorial plane, and so on. That is generally how the corresponding numbers per orbit would go for an orbital mission.

EFFECTS OF ELECTRONS AND PROTONS ON SCIENCE INSTRUMENTS*

Richard H. Parker**

INTRODUCTION

The purpose of this paper is to describe to this workshop some of the effects that the Jovian trapped radiation Design Restraint model (ref. 1) would have on typical science instruments and to suggest specific aspects of the model where an improved understanding would be most beneficial. This paper should be considered as a part of the total picture which is presented together with the three papers by Neil Divine (ref. 2), Jack Barengoltz (ref. 3), and Edward Divita (ref. 4).

Figure 1 shows the TOPS 12L configuration which is the space craft design used in this study (ref. 5). In terms of radiation protection it represents only an attempt to minimize the Radioisotope Thermoelectric Generator radiation interference problems. Table I shows the instrument models used in this study. They represent types only and not the selection of a science payload. The "baseline" set of instruments is shown located on the spacecraft in Figure 1.

These instruments can be divided into two groups, the cruise science and the encounter science. As a generality, the cruise science can more readily afford to lose data during the Jovian trapped radiation belt transit than the encounter science. However, neither group can be allowed to undergo

This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract No. NAS 7-100, sponsored by the National Aeronautics and Space Administration

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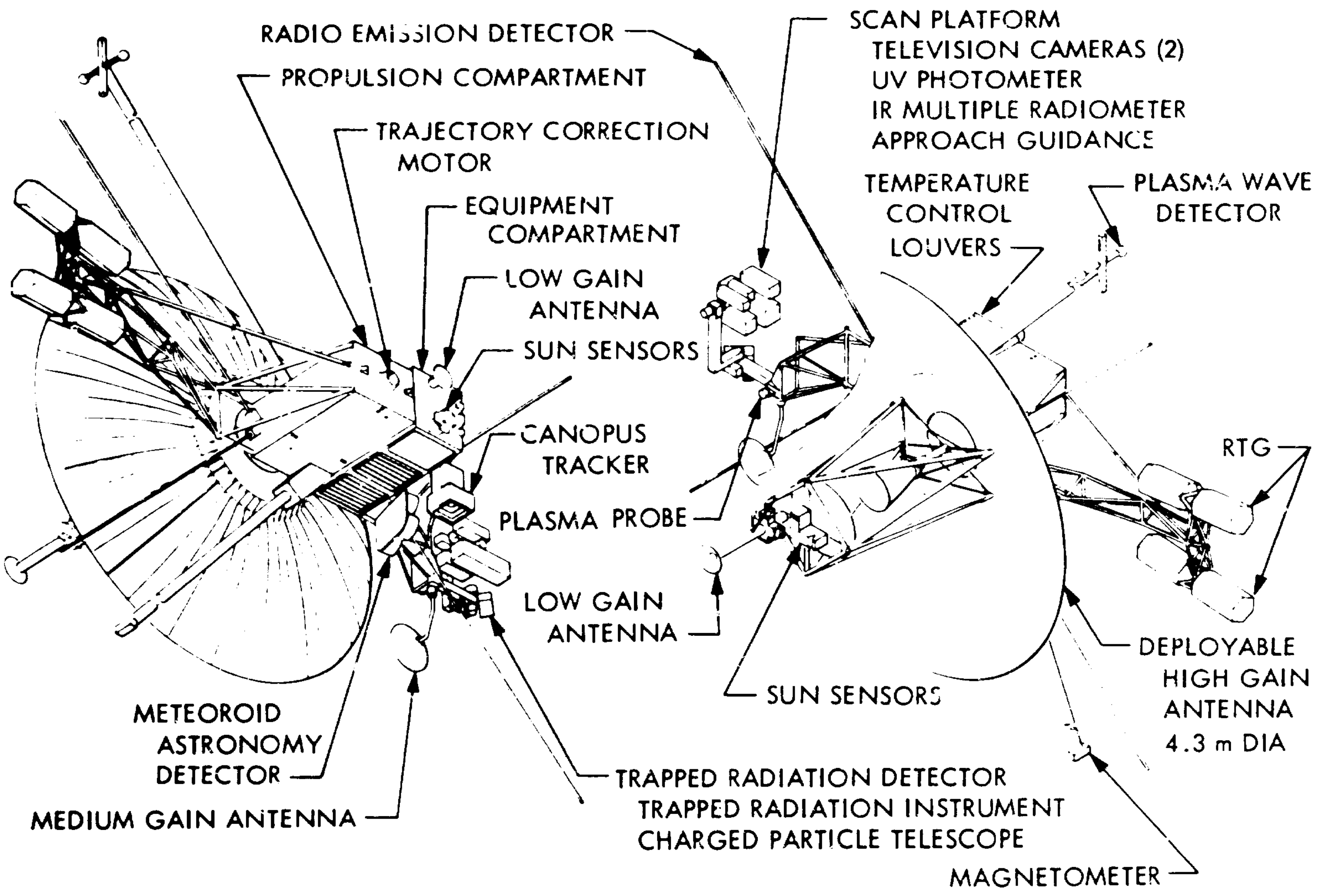


Figure 1. Thermoelectric Outer Planets Spacecraft

Table I. Representative instruments used in radiation effects study

Instrument	Principal Experimenters	Institution (or Mission)
Charged Particle Telescope	J. A. Simpson	(Pioneer F/G)
Cosmic Ray Detector	F. B. McDonald	(Pioneer F/G)
Imaging	TOPS	JPL
Infrared Multiple Radiometer	TOPS	JPL
Meteroid Astronomy Detector	R. K. Soberman	(Pioneer F/G)
Micrometeoroid Detector	O. E. Berg W. H. Kinard	GSFG (Proposed for Pioneer F/G)
Plasma Probe	Wolfe Bame Bridge	(Pioneer F/G) LASL-(MVM) MIT-(MVM)
Plasma Wave	F. L. Scarf	(Proposed for Pioneer F/G)
Radio Astronomy Experiment	J. K. Alexander	(Proposed for Pioneer F/G)
Trapped Radiation Detector	J. A. Van Allen	(Pioneer F/G)
Trapped Radiation Instrument	R. W. Fillius	(Pioneer F/G)
Ultraviolet Photometer	D. Judge	(Pioneer F/G)
Vector Helium Magnetometer	E. J. Smith	(Pioneer F/G)
X-Ray Detector	K. A. Anderson G. Garmire	(Proposed for Pioneer F/G) CIT

significant permanent damage. In detail designs these obvious statements must be modified by the particular experiment objectives. Several reports have been made on the details of the study on which this paper is based (refs. 6, 7, and 8).

The Trapped Radiation Problem

Obviously in designing a sophisticated mission one does not design to the best estimate environment. Translating the philosophy into the highly uncertain radiation environment, Barengoltz has shown the requirements facing the experimenters and the spacecraft designers (ref. 3). Table II shows the results of this effort for all sources including solar flares, solar wind,

Table II. Natural radiation design characteristics and restraints

Radiation Type	Energy Interval (MeV unless otherwise noted)	Maximum Flux (Particles/cm^2-sec)	Fluence (Particles/cm^2)
Proton	3 keV	1.2×10^8	5×10^{15}
	1-3	3.7×10^8	5.7×10^9
	3-10	2.9×10^7	1.7×10^{11}
	10-30	3.9×10^6	9.6×10^{11}
	30-100	2.6×10^6	3.9×10^{12}
	100-300	2.4×10^7	1.6×10^{12}
	300-1000	9.1×10^7	6.1×10^9
	1000-3000	3.0×10^7	4.7×10^8
Electron	0-0.25	4.3×10^9	8×10^{10}
	0.25-3	2.6×10^9	6.4×10^{10}
	3-10	1.2×10^8	5.1×10^{10}
	10-30	2.2×10^7	2.2×10^{11}
	30-100	3.2×10^7	3.2×10^{11}
	100-300	2.5×10^6	2.5×10^{10}

cosmic rays, and the Van Allen belts (ref. 1). The numbers in the dotted boxes are due essentially to the Jovian trapped radiation Design Restraint model. The electrons and protons both effect matter in two ways, ionization and atomic or molecular displacement, although electrons primarily produce ionization effects (ref. 9).

The ionization effects are associated primarily with short term interference problems as opposed to permanent damage. Displacement on the other hand is primarily associated with "permanent" damage. "Permanent" damage may in some instances be annealed, although this often requires heating or electrical changes to be of significance. It is well known that the effects of electrons and protons are not equally severe. Figures 2 and 3 show dE/dx versus E for

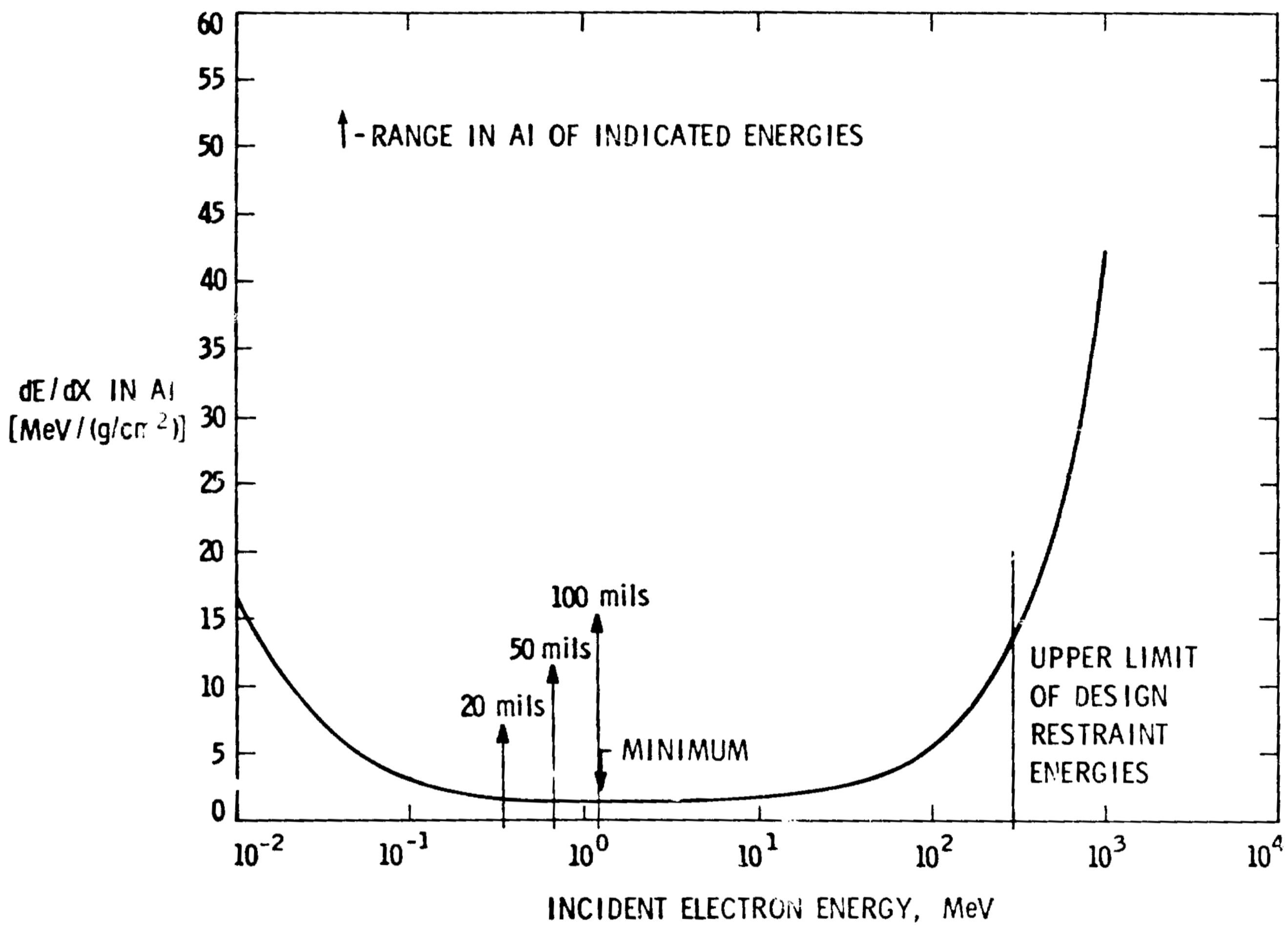


Figure 2. Electron dE/dx in Aluminum vs Incident Electron Energy - (Included are arrows indicating the energy of electrons which will just be stopped by 20, 50 and 100 mils of aluminum. Note that dE/dx (and the damage constant) increases with energy in the energy region of interest (1-300 MeV).)

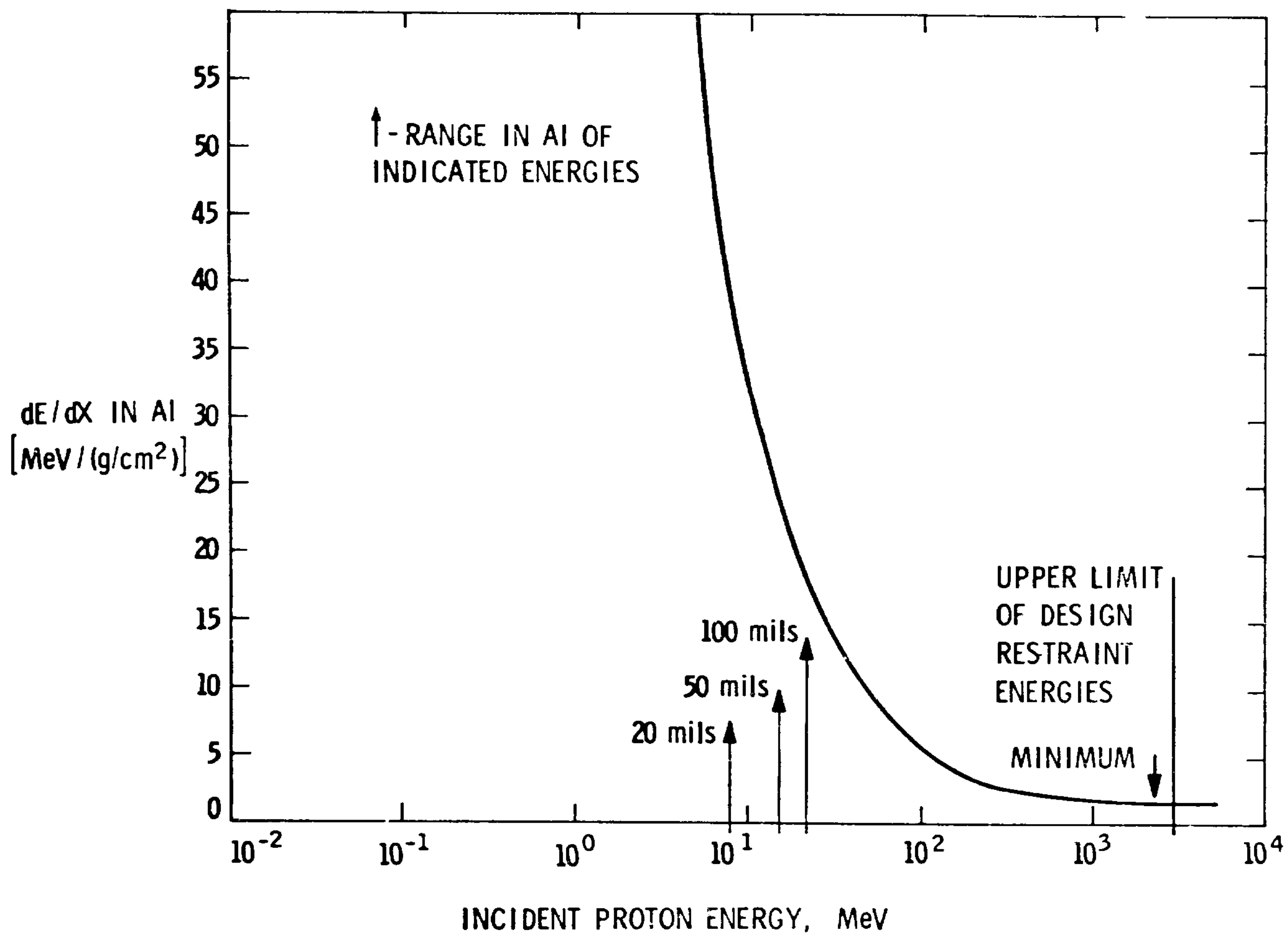


Figure 3. Proton dE/dx in Aluminum vs Incident Proton Energy - (Included are arrows indicating the energy of protons which will just be stopped by 20,50 and 100 mils of aluminum. Note that dE/dx (and the damage constant) decreases with energy in the energy region of interest (1-3000 MeV).)

electrons and protons respectively, and comparing them we see that in the energy regions of interest a proton is a more damaging particle than an electron.

Further, Figures 4 and 5 show the relative ionization damage factor normalized to 3 MeV for electrons and protons respectively. This shows that an energy degraded electron will be less damaging but that an energy degraded proton will be more damaging. Thus shielding may not always be beneficial for the proton problem. For these reasons and the fact that the fluence (time integrated flux) for protons is higher than electrons, only protons will be considered in subsequent discussions.

The specific objectives of an experiment are the primary factors in determining radiation interaction problems. Different instruments with similar detectors can be affected quite differently in the same irradiation if they have different experimental objectives. As an example, consider a bare (no horn) continuous channel multiplier which degrades in gain by an order of magnitude after 10^{10} to 3×10^{11} total counts if the count rate is less than $\sim 3 \times 10^{5}$ counts per second (refs. 10 and 11). Preliminary results of an experiment at JPL indicate that at a flux of 10^{9} electrons per cm^{2} sec (or $\sim 10^{7}$ electrons into the channel per sec) the gain is degraded by 200 after 5×10^{8} total counts. If the device were off during the high flux period (~3 to 4 hours), it appears that it would have the lower rate count life.

None the less, after discussions with the experimenters, certain damage criteria can be placed on specific components which are expected to be most sensitive. Table III shows a partial list of components which may be the most sensitive component in a particular science instrument. Figure 6 is a graph of "damage" thresholds for some of the components. This data is obtained by literature search data (ref. 12), which must be extrapolated to the Design Restraint Model and by a developing test program here at JPL. By comparing this graph with an "equivalent damage" fluence of $\sim 4 \times 10^{12}$ protons-cm^{-2} [(20 MeV) (ref. 13)], we can obtain a qualitative understanding of the problem.

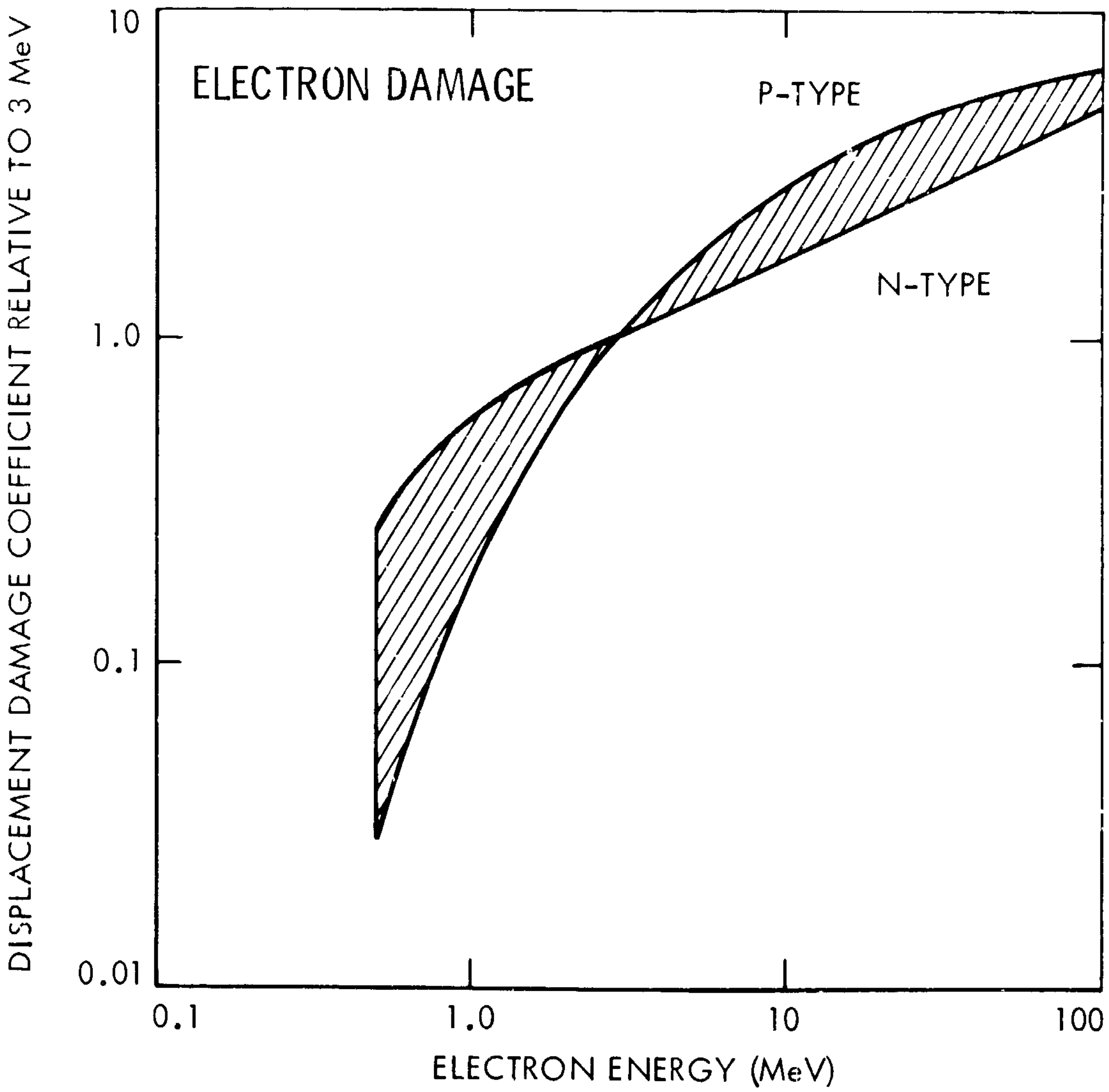


Figure 4. Relative Electron Displacement Damage in Silicon

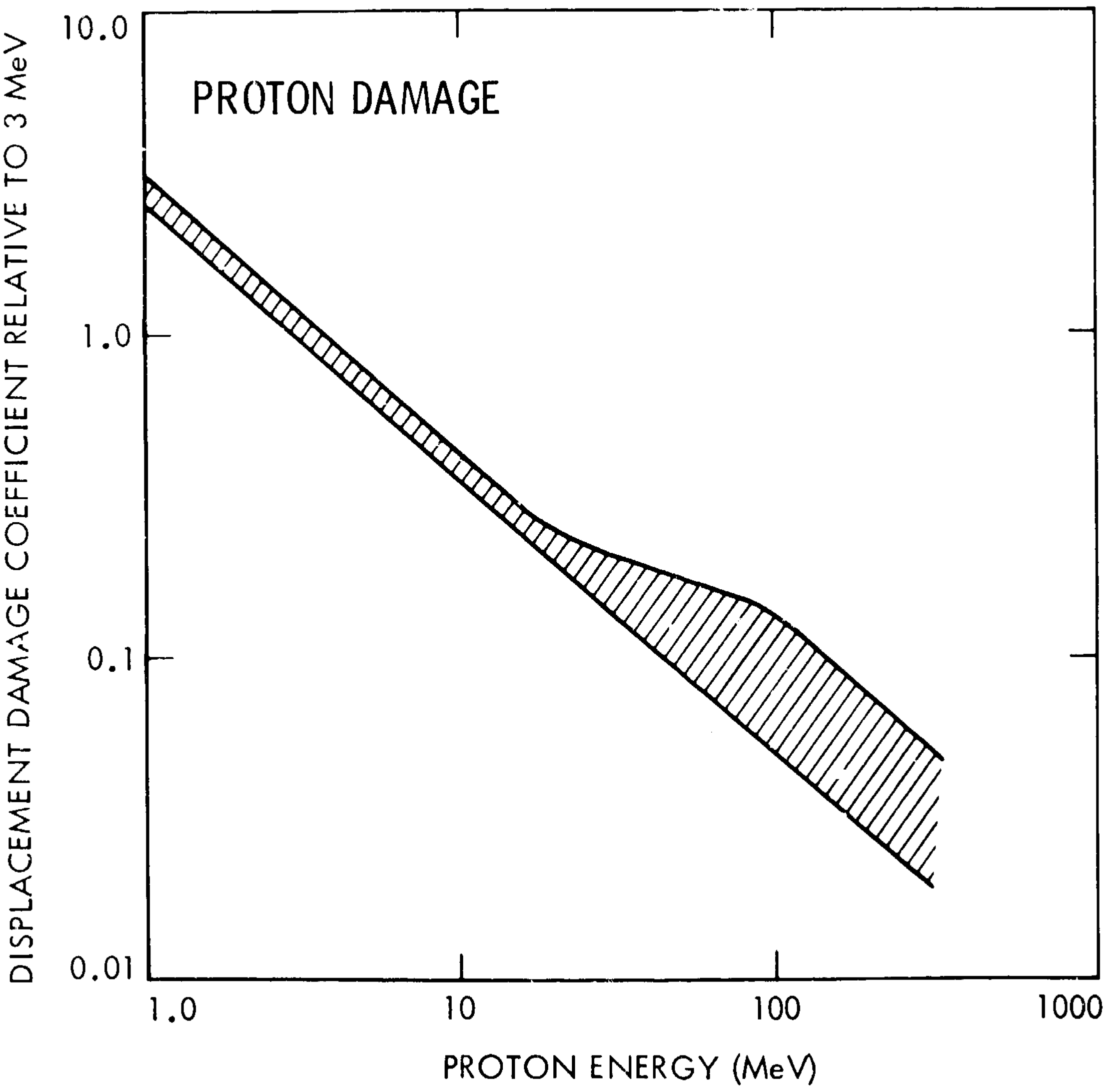
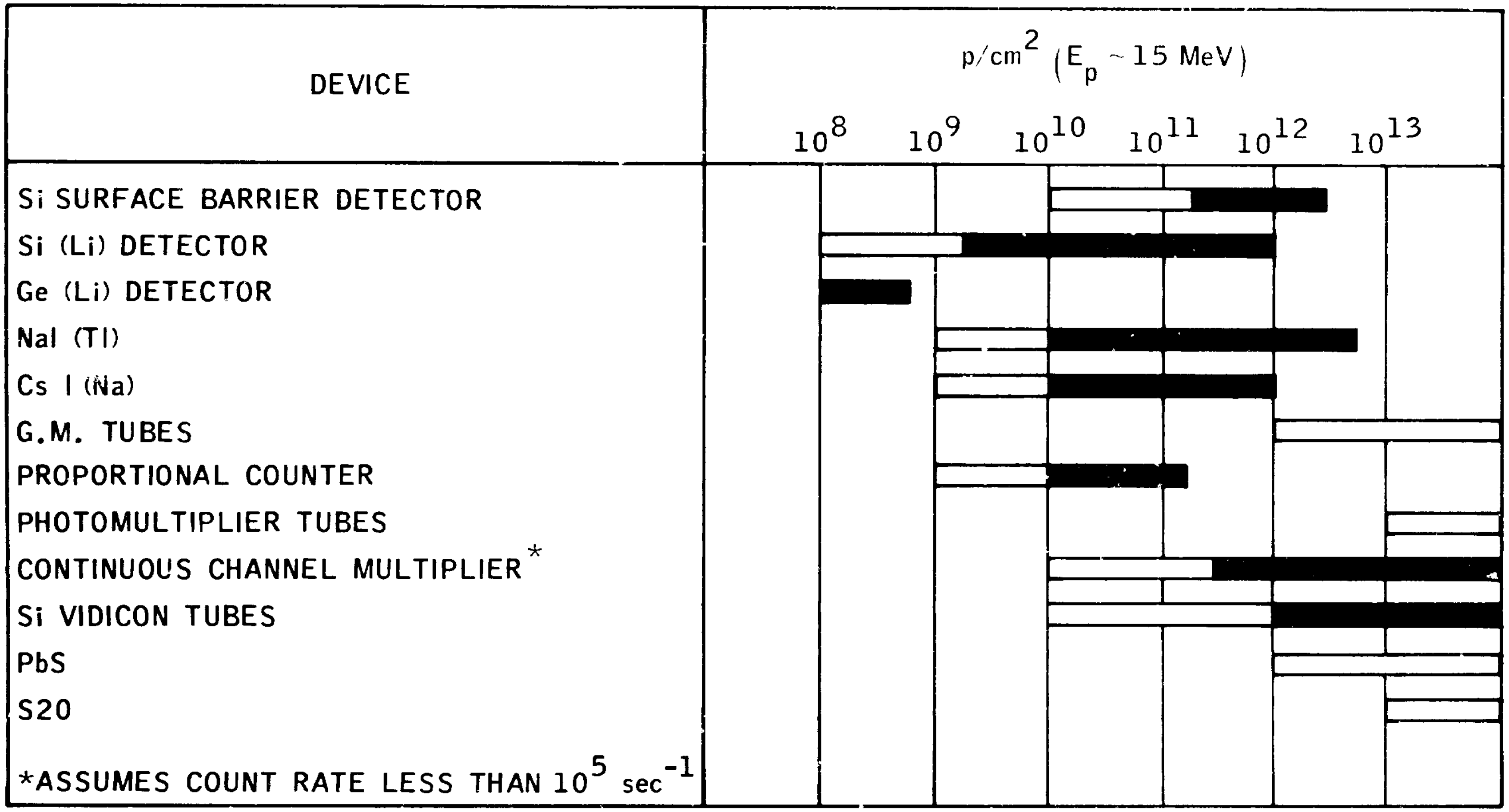


Figure 5. Relative Proton Displacement Damage in Silicon



These damage levels depend strongly on the particular experimental requirements and objectives.

LIGHT TO MODERATE DAMAGE

MODERATE TO SEVERE DAMAGE

Figure 6. Science Instruments' Components Typical Damage Levels

Table III. Radiation-sensitive components which limit instruments either from permanent damage or interference effects

Solid state detectors
Si surface barrier
Si(Li)
Ge(Li)
Scintillators
Na I (Tℓ)
Cs I (Na)
Plastics
Organics
GM tubes
Proportional counters
Photomultiplier tubes
Continuous channel multipliers
Vidicon tube
Emissive and optical materials for:
UV (e.g., S_iO_2 etc., overlap with visible detector materials)
Visible (e.g., S10, etc., ..., >10 types)
IR (e.g., HgCdTe; CdS, MgO, .. , >20 types
Electronics

Several of the science instrument types will be limited by general electronic components rather than any specialized device. Figure 7 shows proton "damage" thresholds for typical types of electronic devices. Again, one can compare the damage thresholds to the design restraint spectrum or the equivalent monoenergetic fluence level to obtain a feeling of the problem. Doing this for these components clearly shows a severe hazard to any science instrument. At this point, it should be pointed out that interference effects to imaging, ultra violet and other encounter instruments are not considered here, but only the survival of the instruments for the succeeding encounters.

Possible Protective Measures

There are, of course, many ways to protect an instrument from radiation interference, most of which are limited for flight instruments. First, one selects components which are as radiation resistant as possible. Since we have gamma and neutron radiation, as well as the charged particle, this may not require similar techniques for the various radiation types. Currently, JPL is looking into this for electronic parts.

A second technique is "electronic shielding," that is, using a difference in the desired signal shape and the undesired signal shapes to segregate them. Examples are the pulse risetimes, the pulse widths, and the pulse heights. If the desired signal is analogue, then simply ignoring rapid changes will remove the unwanted signals or if the undesired signal becomes analogue, (high flux) and the desired signals are pulses, one can use a-c coupling. Also, in this category is an active shield such as a scintillator cylinder of the Charged Particle Telescope. These techniques will be employed where possible.

A third method is orientation and location on the spacecraft. For an isotropic irradiation orientation of a component is not too useful, but location may be useful for non-highly penetrating particles. Here one uses less susceptible materials to shield the more sensitive one. Look angle of the instruments is a limitation to this method for science instruments. This method requires accurate flux versus energy information at the various positions around Jupiter which this workshop hopefully will develop.

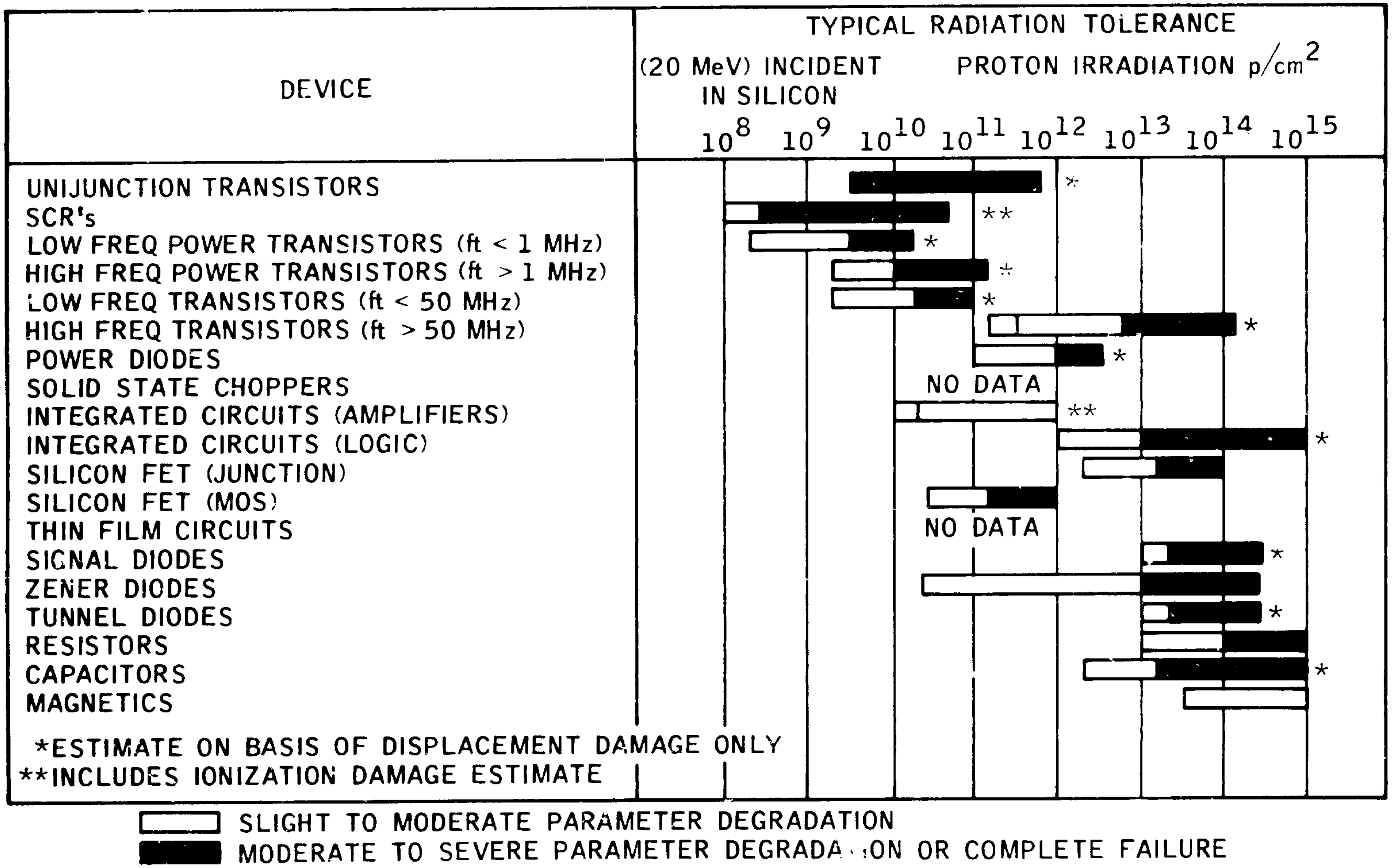


Figure 7. Survey of Component Proton Degradation

The fourth method is additional passive shields to protect specific components. Again, the requirements of a specific solid angle viewing limits this method for many instruments (some of which have the scientific objective of measuring the Jovian trapped radiation).

A brief look at the shielding possibilities of our current Design Restraint model is not very encouraging. Figure 8 shows the effects of gold shields (chosen as an example element only) on the Design Restraint proton spectrum (integrated along a specific trajectory (ref. 3)). Notice that the lower energy proton levels actually increase due to the larger number of originally higher energy protons which are down graded to the lower energies. Referring back to either Figure 3 or 5, one can show that a more severe damage problem will be created with the "shielded" spectrum than the unshielded for up to 100 mils of gold. To protect a 3-inch radius sphere with 100 mils requires a

$$4\,\frac{\pi}{3}\left[(3.1)^3 - 3^3\right](\mathrm{in}^3)\left[(2.54)^3\left(\frac{\mathrm{cm}^3}{\mathrm{in}^3}\right)19.3\left(\frac{\mathrm{gm}}{\mathrm{cm}^3}\right)\right] = 3.8\ \mathrm{kg}\ (\sim 8.4\ \mathrm{lbs}) \quad ,$$

and for a 5 inch radius 9.8 kg (~21.7 lbs). On a mass limited spacecraft, one can't afford to "spend" that much mass just to get back near the original situation. More detailed studies may improve this picture later. These detailed designs of shields will clearly be invalid if the trapped radiation model changes and, therefore, a consensus of opinion now will aid the motivation to develop these detailed trade off design studies.

Summary of Current Options

There are, of course, significant uncertainties in radiation effects. These are being studied now in the hope of understanding and remedying the deleterious effects. If we assume the effects are exactly known to the flight experimenter, several options are available and are listed below in decreasing order of attractiveness. First, to attempt to lower the Design Restraints without compromising the success of the missions. This can be done in several ways which would be helpful.

Heavy line shows unshielded Jovian trapped proton fluence for a Grand Tour trajectory with a $3R_J$ periapsis.

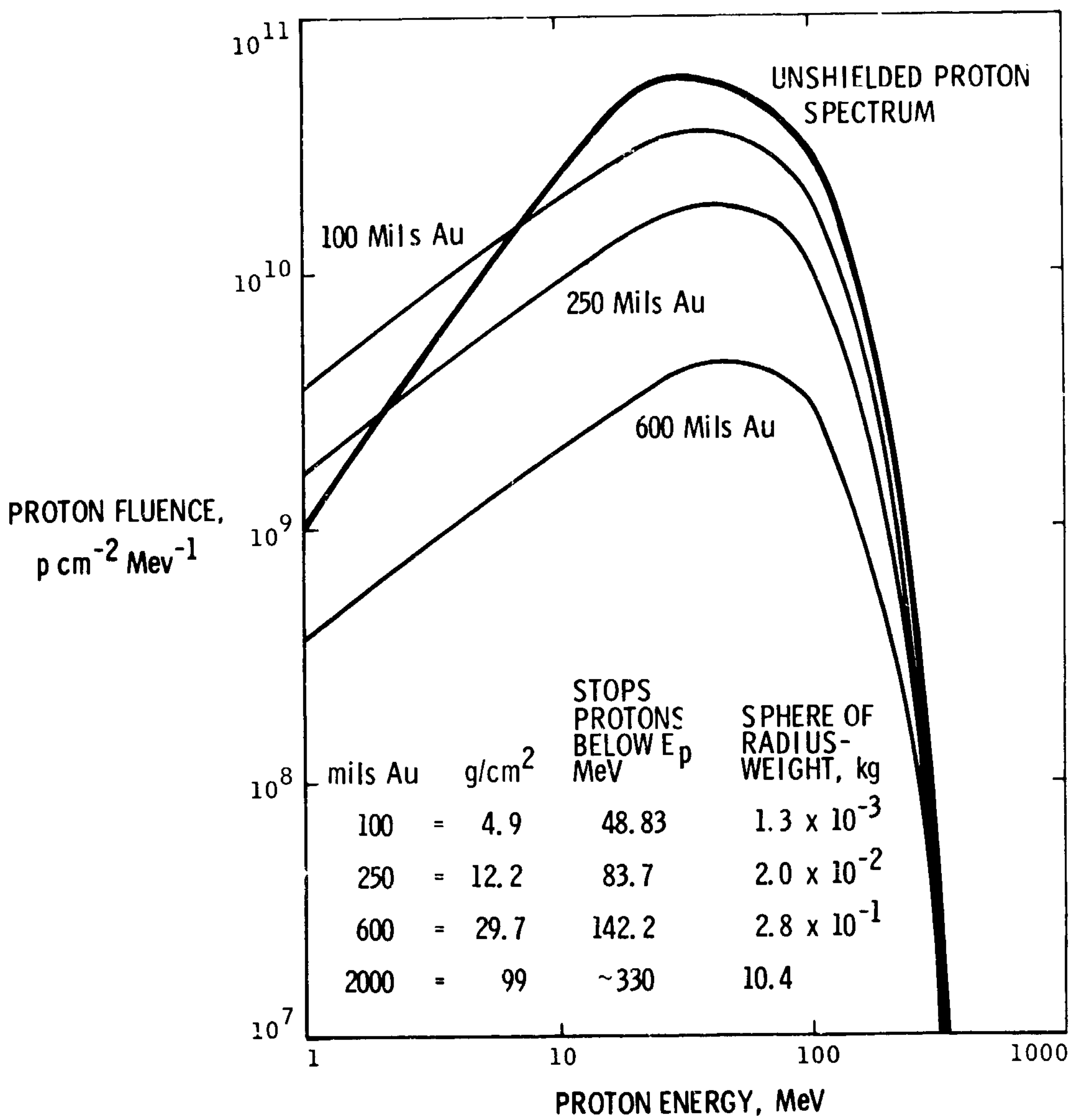


Figure 8. The Effects on Proton Fluence of Shielding on a Grand Tour Trajectory

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(1) a reduction in the electron and proton number density as a function of L (McIllwain Coordinates)

(2) a change in the energy spectra such as a reduction of the most probable energy, an upper limit energy at a relatively low energy level or a more rapid decrease with energy

(3) a combination of 1 and 2

The development of this option is the purpose of the workshop.

A second option is to trade off experiment objectives for increased reliability by one or more techniques previously outlined. This option reduces the benefits derived from the mission to the scientific community.

A third option would be to alter the trajectory (i.e., change the multiple encounter missions). This also requires a better understanding of $\Phi(L)$ which this workshop hopefully will provide. Here one is also trading off time to final encounter which interacts with reliability.

A fourth option would be to remove sensitive instruments from the payload, completely losing the benefits to the scientific community. Detailed studies must soon be started to optimize the many parameters involved in designing the instruments chosen for the payload. Indeed, the Outer Planets Grand Tour Science Steering Group is currently deciding on a payload recommendations which will be made based partly on radiation reliability. Thus, an accepted Jovian trapped radiation Design Restraint model is urgently needed to continue the design of reliable science instruments.

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DISCUSSION

DR. AXFORD: You mentioned damage. Do you have any idea about what experiments just wouldn't be working in terms of damage?

MR. PARKER: Well, in terms of the design-restraint models, I don't think any of the instruments would be working. A list of how hard they are is available. But, generally, if an instrument uses something like a germanium lithium drifted detector, it would be the first to go.

Again, this is something that is quite strongly dependent on the particular instrument objectives. Interference problems for nearly all instruments will be severe in the Jupiter environment. However, the problem I am trying to solve is survivability rather than interference.

DR. TRAINOR: The upper-limit model will also bother many of your spacecraft systems.

MR. PARKER: As you can tell from the damage levels on electronic parts, if the spacecraft bus has any electronic parts in it, it will probably have some damage.

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IMPACT OF JOVIAN RADIATION ENVIRONMENTAL HAZARD ON SPACECRAFT AND MISSION DEVELOPMENT DESIGN*

Edward Divita**

Basically, my presentation is a summary identifying the impact that the environments which you have heard described today have on our spacecraft design. The spacecraft that we currently have designed is in a developmental phase. The design which I will show is the Thermoelectric Outer Planets Spacecraft (TOPS). It is essentially a Grand-Tour versatile spacecraft. We are designing it to survive the radiation of Jupiter, and also so that it can successfully tour the remainder of the outer planets. To get you involved in how your workshop results might influence us, I will show you how the current radiation environment affects the design. Various design phases will be discussed. Questions like where we are, what we have considered, what we haven't considered, and what we are doing right now will be answered.

You are invited to stop me at any time and ask questions or promote discussion throughout this presentation. Most of the data you may have seen; or it will be complementary to the same type of design data that you may have seen. This presentation will be an interpretation of what you have seen relative to how the designer should hear it, should view it, and at least, consider it in his design.

In Figure 1, I would like to identify the environmental impacts. As you can see, they are of a variety of types. There is a significant impact on system design, which is basically the phase we are in right now--that is, the developmental portion of that phase.

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*This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract No. NAS 7-100, sponsored by the National Aeronautics and Space Administration.

**Jet Propulsion Laboratory, Pasadena, California 91103.

- System Design
- Testing
- Long-Life

May Impose New and Unique Requirements

- Materials
  - Piece-Parts
    - Components
      - Assemblies
        - Integrated System
          - Life
- Facilities
  - Missions
    - Launch Vehicles
      - Science

Figure 1. Impact of Jovian Radiation Environmental Hazards on Spacecraft

In addition, there is a significant impact on testing, that is, previous testing results, what they mean to us, and some developmental testing that we have underway. Finally, the radiation environment potentially impacts the ability of assemblies to survive long-life missions beyond Jupiter. If we are going to have to survive the Jupiter radiation environment, we anticipate another six years of mission beyond that time. We would like to know what surviving the Jovian radiation means to the spacecraft in terms of its useful life.

As a result, you can see that there are many new and unique requirements on materials, piece-parts, components, assemblies, the integrated system, and spacecraft life. In particular, what do these new requirements mean to us as specifiers and designers of what we need for test facilities? Also, what are the mission influences related to the radiation environment for that portion of the mission at Jupiter (the flyby)? I think several speakers have identified these flybys as being anywhere from a tenth of an R_J to 5 or 6 R_J from the surface of the planet. Finally, what do the new environmental requirements mean to us in terms of launch vehicle requirements? Indeed, if we require mass shielding, what does this mass requirement demand in the launch vehicle capability?

In Figure 2, I would like to give you an idea of what we have been doing in the past couple of years in system environmental design. We have been identifying our interfaces, both from a science and engineering standpoint, and relating them to our configuration designers and system designers. The designers take into account the various things that we know about the environment and identify its impact on the spacecraft design, both for the scientists and the engineers. I might point out that, indeed, we do anticipate problems if we have to live with the design restraints we have now. We anticipate problems with the engineering subsystems as well as the science instruments.

We are also looking at various aspects of tradeoffs for the design, the possibility of shielding, which we have identified. I will identify, again, the potential use of shielding. Again, we have not performed the

INTERFACES - SCIENCE AND ENGINEERING WITH CONFIGURATION AND SYSTEM DESIGNERS

TRADEOFFS - SHIELDING, ORIENTATION, RADIATION HARDENING, SEPARATION AND LOCATION

DEVELOPMENTAL TESTS - ASSESSMENT OF ENVIRONMENT SENSITIVE EQUIPMENT

DESIGN INTEGRATION - OVERDESIGN, REDUNDANCY, REDESIGN

COMBINED ENVIRONMENTAL EFFECTS - TESTING AND REDESIGN

TEST AND DESIGN VERIFICATION - ALL LEVELS OF EQUIPMENT

Figure 2. System Environmental Design

detailed design that goes along with the shielding; the possibility of using orientation; a good possibility of using radiation hardening, if we can demonstrate that it has a use for our new environment; and the use of separation distance and location and what they mean to spacecraft design. In addition, there are things that we have been doing in developmental tests. That is, we are, in a very small way, assessing how this radiation environment, as we have defined it, influences our selection of piece-parts and some science instrument components.

On design integration, I think that the kinds of things that we must consider if we are going to satisfy the radiation environment and long life are overdesign, redundancy, and, as we go along, redesign. Essentially, we are going to have to satisfy a combined set of environmental requirements. We haven't looked at that problem yet. But it means answering the question, what about all the other environments--environments that we may have to satisfy along with the radiation environments? What do these environments mean to us in terms of testing, how we test, and what it means to the designers in terms of redesign? And, of course, in the later phases, the formal testing phase of the project, you have test and design verification tasks. This will include testing a variety of sensitive equipment at all levels of hardware. Each may have to be tested to ensure a proper design.

Figure 3 identifies some of the features of the TOPS 12L configuration which you have seen. Since you have seen it, you probably have some questions about it. The science instruments are, as well as the engineering electronics compartment, located in the configuration given in Figure 3. Note that we have not specified any shielding for the Jovian radiation field for this design. I will, however, identify the potential use of shielding. The only thing that we have done so far relative to the design is we have taken advantage of putting the electronics for the engineering subsystems behind the propulsion compartment and the science instruments behind the electronics compartment or at some additional distance beyond the electronics compartment. If there is a shielding requirement for more sensitive assemblies we have the option of packaging them in such a way that we can take account of the shielding afforded by the large propulsion and electronics compartments

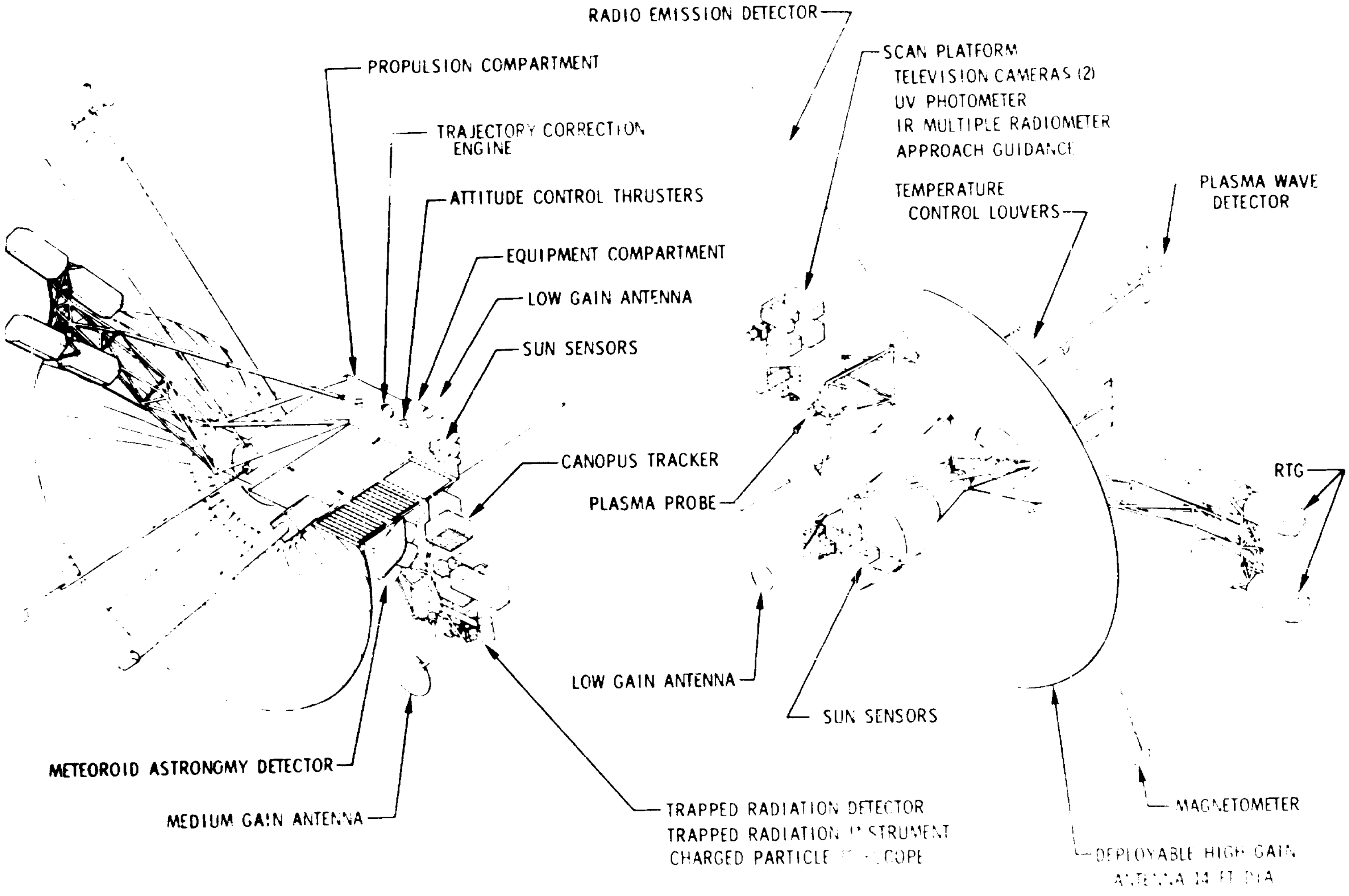

Figure 3. Thermoelectric Outer Planet Spacecraft

CONFIGURATION 12L (WITH REPRESENTATIVE PAYLOAD) and the shielding afforded by more radiation resistant assemblies. I might point out that orientation provides inherent shielding. So, by arranging the sensitive devices to minimize their exposure, shielding is provided. Basically, orientation as a design approach has been used to satisfy the RTG radiation requirements. However, my intent is to relate to you that the system has not accounted for mass shielding as yet. There is a phase of detail design that will show what can be done with shielding for the configuration.

Figure 4 shows the current radiation design restraints including those established in the Jupiter radiation belt flyby mission, JSP76. You have had these restraints defined to you previously by R. Parker. The discussion of the levels will be approached from a designer's viewpoint. The environment that I am concerned with is the Jovian radiation part as shown which dominates the energy region 1-300 MeV for electrons and the energy region 3-3000 MeV for protons of the design restraints. Let me elaborate on what these numbers are and where they come from. Earlier today you saw a presentation on a set of upper limits and nominal models or best estimates that Neil Divine gave you. I think Jack Barengoltz pointed them out again. I think what I want to do is start off with some definitions. A design restraint as we use it is essentially the upper-limit model of the radiation belts. It contains the identical uncertainty that Neil Divine pointed out, both in energy and in fluence. I think he gave an estimate of something like a factor of 10 for the electrons and a factor of one hundred for the protons between the best estimate and the upper-limit model.

The levels in Figure 4 are the restraints based on that upper-limit model. Also, some levels that were pointed out to you earlier either by Jack Barengoltz or Dick Parker which were test levels derived from these restraints by taking an equivalent total fluence at a given energy are based on a displacement damage versus energy curve.

Figure 5 contains data which allows one to recall specifics on range-energy cutoff data. I think it is important to look at this range-energy cutoff information from a different standpoint, because each of these above listed mechanisms will influence the interactions in an electronic part

RADIATION TYPE	ENERGY INTERVAL (MeV UNLESS OTHERWISE NOTED)	MAXIMUM FLUX (PARTICLES/cm^2-sec)	FLUENCE (PARTICLES/cm^2)
PROTON	3 keV	1.2×10^8	5×10^{15}
	1-3	3.7×10^8	5.7×10^9
	3-10	2.9×10^7	1.7×10^{11}
	10-30	3.9×10^6	9.6×10^{11}
	30-100	2.6×10^6	3.9×10^{12}
	100-300	2.4×10^7	1.6×10^{12}
	300-1000	9.1×10^7	6.1×10^9
	1000-3000	3.0×10^7	4.7×10^8
ELECTRON	0-.25	4.3×10^9	8×10^{10}
	.25-3	2.6×10^9	6.4×10^{10}
	3-10	1.2×10^8	5.1×10^{10}
	10-30	2.2×10^7	2.2×10^{11}
	30-100	3.2×10^7	3.2×10^{11}
	100-300	2.5×10^6	2.5×10^{10}

Figure 4. Natural Radiation Design Characteristics and Restraints

IONIZATION

DISPLACEMENT

SCIENCE INTERFERENCE

PARTICLE TRANSMISSION/ATTENUATION

ELECTRONS		PROTONS	
ENERGY (MEV)	RANGE-Al (MILS)	ENERGY (MEV)	RANGE-Al (MILS)
≤ 0.5	25	≤ 10	25
≤ 1.5	84	≤ 20	84
≤ 10	800	≤ 100	1300
≤ 20	1500	≤ 200	4400

Figure 5. Radiation Interactions and Effects

or science component. What I want to do with the energy cutoff information is to identify what the potentially effective spacecraft thicknesses would do to stop protons and electrons below given energies. This has been pointed out, but 50 to 100 mils was generally used to represent the spacecraft afforded shielding. The number flux at 1½ MeV electrons are shielded and everything below that are shielded with about 84 mils. Note, however, when you go to 10 MeV electrons, you need about eight-tenths of an inch of aluminum to stop the $\leq$10 MeV particles. The same deductions can be obtained for the protons using the information in Figure 5. I think this has been pointed out a couple of times--but for protons one sees for 15 MeV, it's 50 mils, for 20 MeV, it's 84 mils. When the cutoff energy is a hundred MeV, the required thickness is 1.3 inches of aluminum. These large effective thicknesses are not available when you consider spacecraft afforded shielding unless you can identify in the electronics package that you get a large thickness provided through modular packaging of less sensitive components in the system.

Basically, the components that we have looked at so far --for at least the protons--generally, all are sensitive to the levels that we showed you for the design restraints. Figure 6 shows an idea of what this means in terms of the current electron design restraints. Figure 6 shows the percent of electrons with energies greater than E as a function of electron energy and aluminum thickness. Eighty-four mils essentially knocks out about four or five percent of the spectrum. Eight hundred mils knocks out about 15 percent of the spectrum. You can see that you have quite a large spectrum to deal with if you are talking about the design restraint. Again, I might just point out that the best estimate model fluence is about--for the electrons--an order of magnitude less than the design restraint.

On Figure 7, I show the same relationships for protons. Again, you see that for the 84 mils, you see very little influence by the nominal or minimum spacecraft shielding. The shielding would have to cutoff about a hundred MeV which requires 1.3 inches before you see only 25 percent remainder of the fluence or 75 percent reduction in the total proton fluence. That is not a significant reduction when you talk about this design restraint being 2 orders of magnitude above the best estimate model.

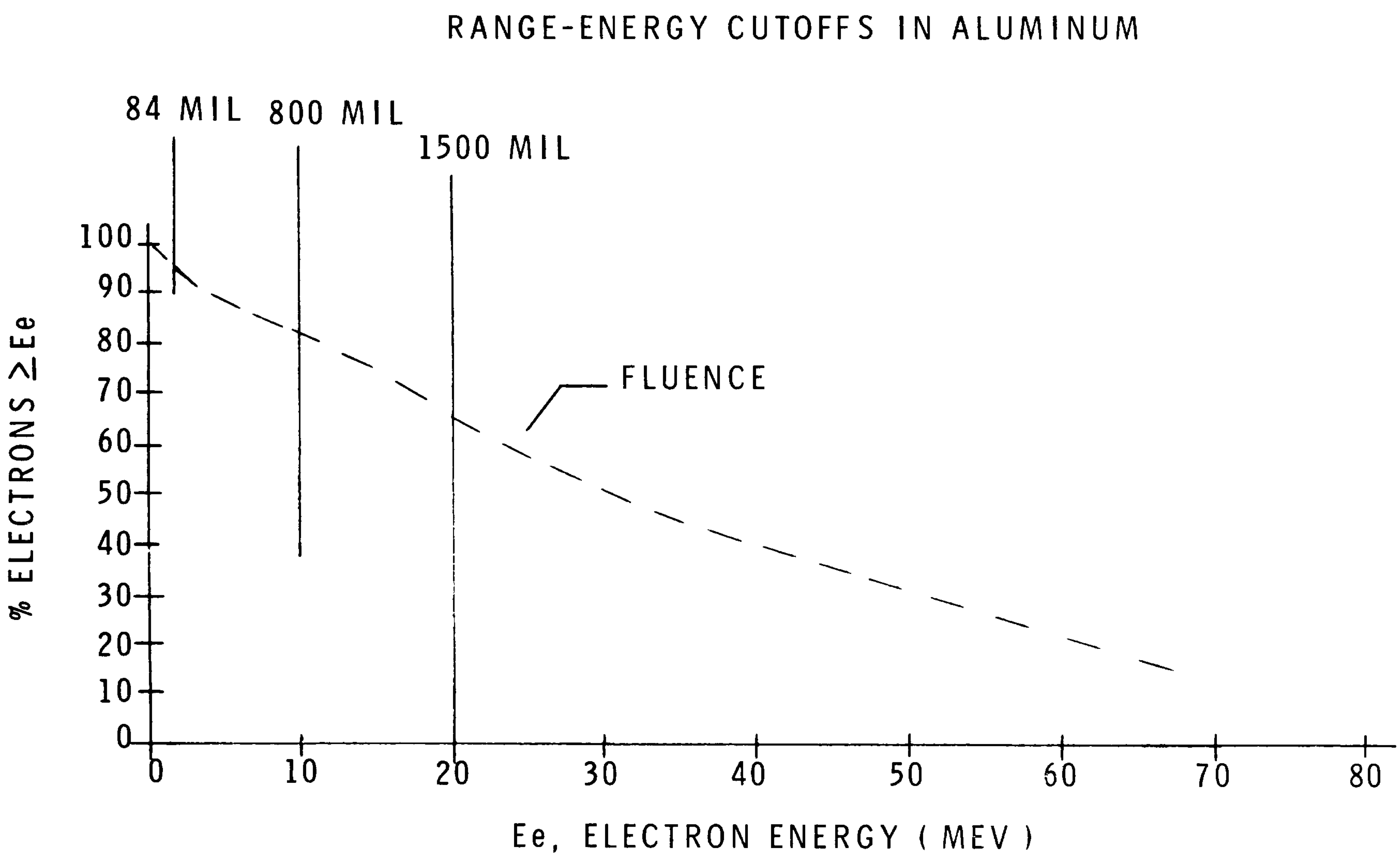

Figure 6. Percent Electrons Above Electron Energy Specified for TOPS Restraints

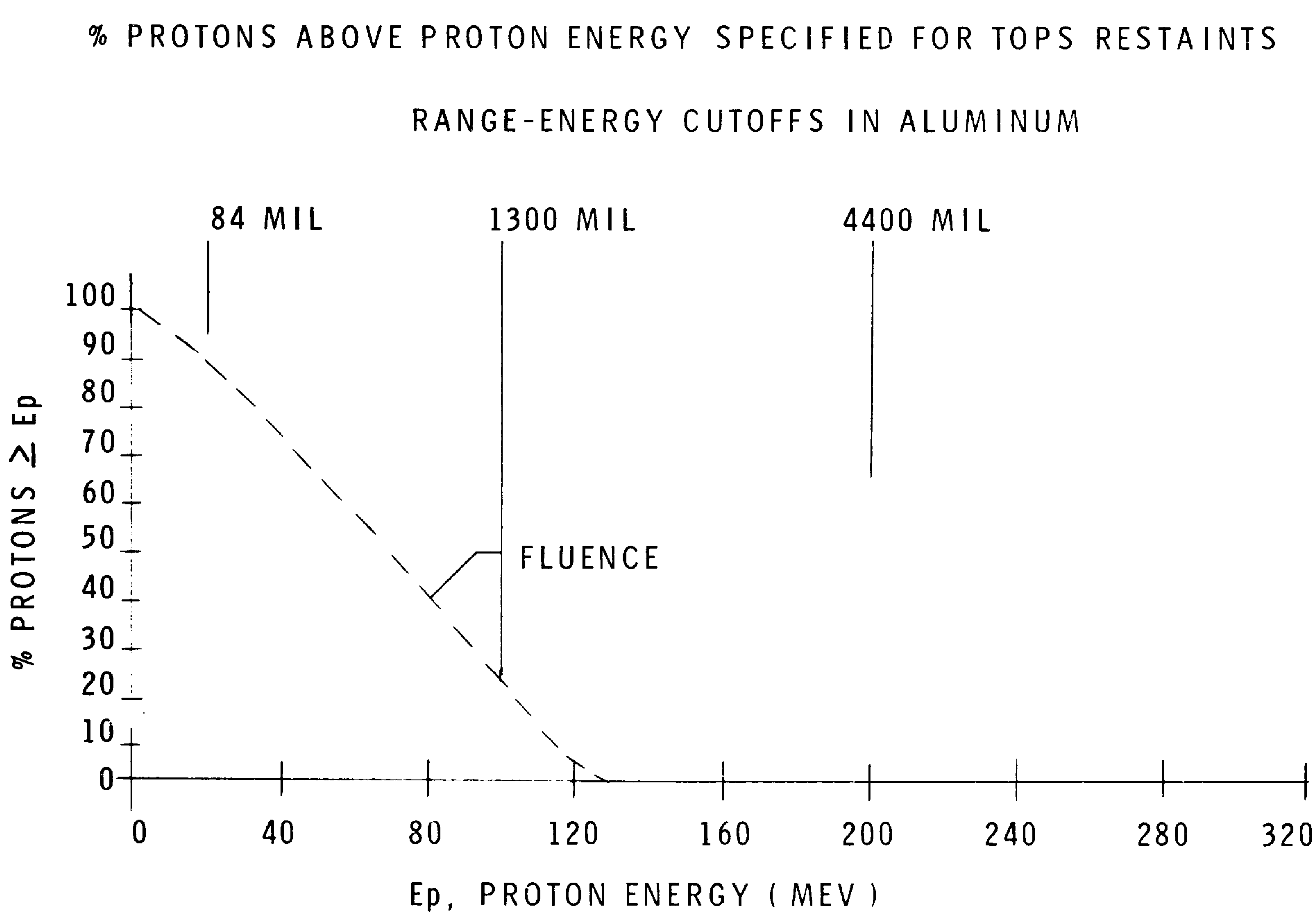

Figure 7. Percent Protons Above Proton Energy Specified for TOPS Restraints

I hope I have given you an idea of what is required in designing, or attempting to design, to the design restraints and what it means in terms of effective shielding. Now, to point out some of the problems, or at least the essential problems, that we encountered by trying to do some of the things that might help us. That is, if we try to use shielding, separation distance, orientation, in system design what does it mean to the spacecraft designer?

Figure 8 contains a list of some of the design integration problems. The designer may have a spacecraft attitude control problem. Also, the designer has to make sure he gets proper orientation and proper weight distributions for his spacecraft. It also means we have to make sure that the science instruments have the required look-angles for that given instrument. These are fields of view that we have to account for, and possibly deploys and scans; some of which you have seen identified on the TOPS configuration 12L. For the engineering subsystems, there may be packaging problems. If we package the subsystems so that only the radiation-resistant subsystems are in the outside shell, then that may be an integration problem, because I don't know that it can be accomplished. Again, applying system tradeoff to satisfy radiation requirements can impact the antenna design. The tradeoffs that are introduced may cause problems with communication and navigation. Therefore, for the radiation environments, we have to consider the overall system design integration. Trying to satisfy the Jupiter radiation belt design restraint may be a problem.

In Figure 9, I present some of the radiation testing considerations and discuss what we have been doing relative to TOPS and the impact that test results may have on the Jupiter flyby missions. Our guiding concept during the TOPS Project has been to develop and select the parts and components which will satisfy a standard set of environmental test requirements. Prior to TOPS, we did not have a set of standard radiation test requirements. Now, we have developed a standard set of radiation test requirements based on the design restraints and test levels.

- SPACECRAFT ATTITUDE CONTROL
- SCIENCE LOOK ANGLES, FIELDS OF VIEW AND DEPLOYMENTS AND SCANS
- ENGINEERING SUBSYSTEMS - PACKAGING, COMMUNICATION, NAVIGATION
- OVERALL SYSTEM DESIGN AND INTEGRATION

Figure 8. Shielding, Separation Distance and Orientation Effects

- GUIDING CONCEPT - DEVELOP AND SELECT PIECE-PARTS AND COMPONENTS WHICH SATISFY A STANDARD SET OF ENVIRONMENTAL TEST REQUIREMENTS
- IMPLEMENTATION - SIMULATE JOVIAN RADIATION AND MEASURE CRITICAL PARAMETERS BEFORE, DURING AND AFTER TEST
- RESULT - DEVICE PERFORMANCE DATA FOR DESIGN

Figure 9. Environmental Testing

When you study these requirements, you will see that we are going to have to perform radiation tests to qualify parts and higher levels of equipment. There is no radiation testing data available that would satisfy this set of test requirements even from a developmental testing standpoint. We may use data that is available as a guideline, but we are going to have to develop test requirements for these environments. Our approach in the developmental stage is to start doing some of the testing and evaluate how these environmental test requirements affect the parts.

Let me give you an idea of what that means in terms of what we have accomplished. From Figure 10, one may determine the influence of Jovian radiation on the state-of-the-art parts data, and use these results as guidelines to select parts which should be tested in a formal test program. I will point out the ranges of radiation thresholds because I think it is important that you get an idea of some of the uncertainties in threshold data given in Figure 10. Also, I want to stress that device usage, as far as we know now on the basis of our test and detail tests that relate to these kinds of environment, is important in both electron and proton radiation environments. How that device is used is an important consideration in determining how much damage (what the threshold level of damage is) or what you have to do in parameter selection to use the device in a subsystem.

In Figures 11 and 12, I would like to summarize the piece-part radiation threshold tables. One for protons and one for electrons. Let me identify what we have for electrons. Figure 11 contains a list of the total fluence of electrons for 1 to 3 MeV equivalences of damage for various part types. I have placed on this bargraph the TOPS design restraint and our best estimate model of the environment. This model is based on the NASA Monograph--The Planet Jupiter 1970. Following the design restraint level for the few parts that we have radiation data for electrons, you see there is a potential problem to some of the low frequency transistors and to the J-FET devices and to the MOS-FET (metal oxide silicon-field effect transistor) devices. In Figure 11, you see that some parts may really be in trouble with electrons. I might point out that, again, from looking at the best estimate, we potentially have problems only with the MOS-FET device. I think there was a question asked

- PIECE-PARTS FUNCTIONAL BEHAVIOR IN PROTON AND ELECTRON ENVIRONMENTS
- RADIATION EFFECTS
  - CHANGES IN PROPERTIES
  - INDUCED RADIOACTIVITY AND INTERFERENCE
  - TRANSIENTS
- PARTS APPLICATIONS IN CIRCUITS AND ASSEMBLIES
- "OVER-DESIGN" - REDUNDANCY, DERATING AND HARDENING
- OPERATIONAL USE
- INHERENT PROTECTION
- ADDITIONAL PROTECTION

Figure 10. Design Considerations

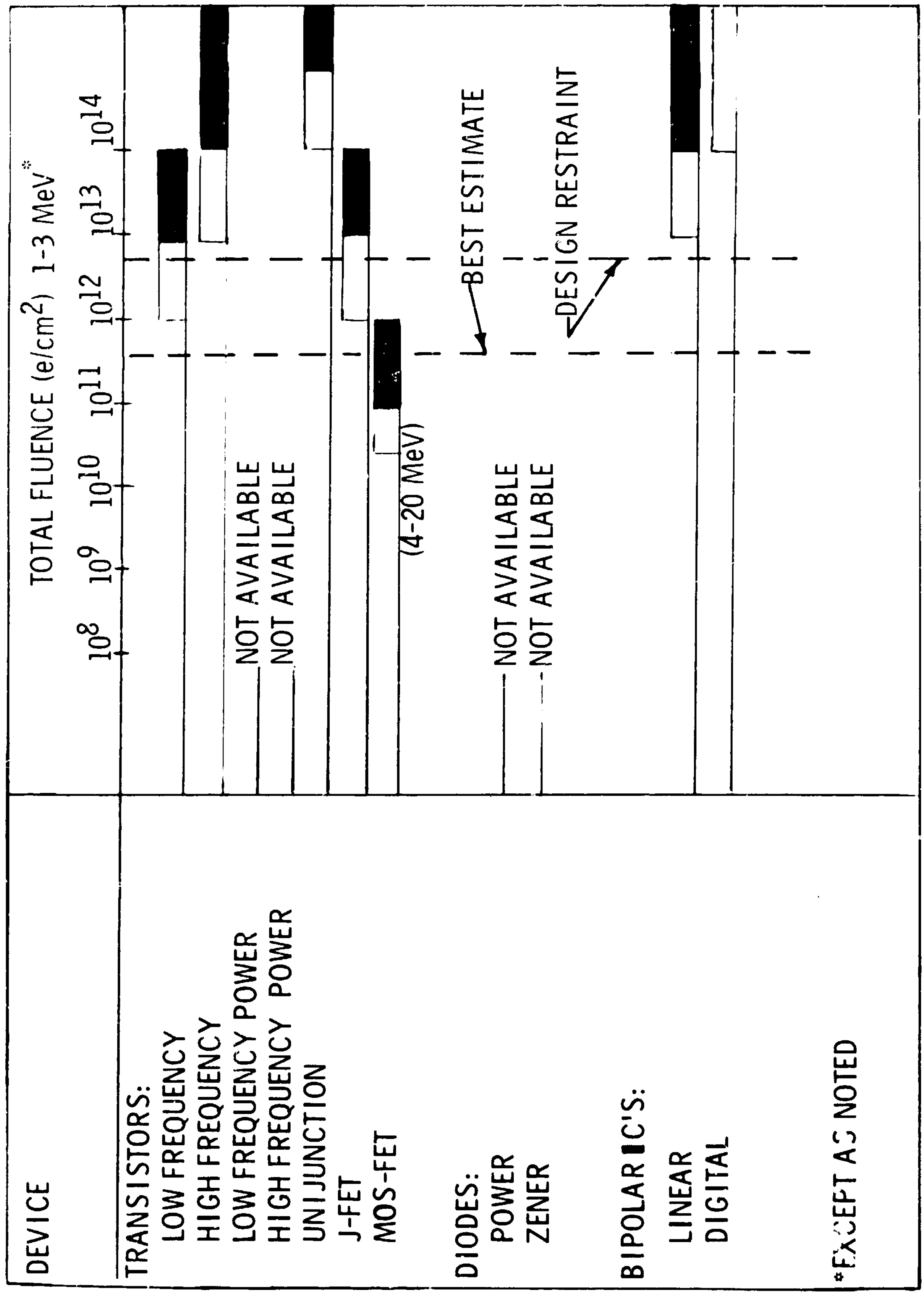

Figure 11. Survey of Part Degradation (Electrons)

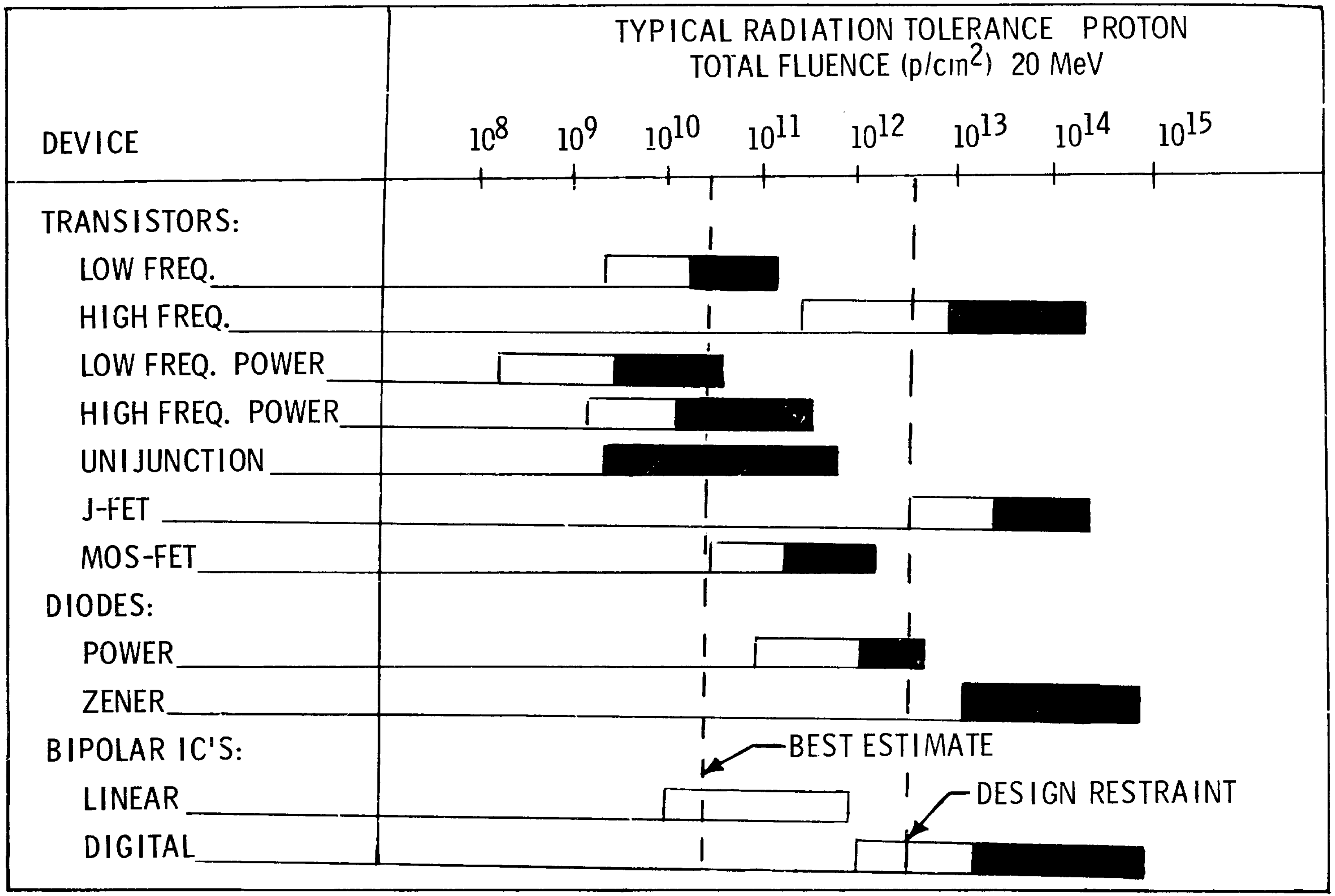

Figure 12. Survey of Part Degradation (Protons)

earlier, "Are we concerned with electrons?" I think the answer is "yes," we are, because this table is not filled. More important, it is not filled with data on the usage of these devices. How they will be use is important so we would like to see more electron data.

DISCUSSION

DR. TRAINOR: Can I comment, please, before that goes away? The MOS-FET--these curves should all be taken as a sort of--

MR. DIVITA: Guidelines.

DR. TRAINOR: --Guidelines sort of thing, because, for instance, on MOS-FET, the Goddard Space Flight Center custom line of MOS-FET made by AMI conventionally tolerates 10^{13} electrons per cm^2, readily. That is a good device.

DR. BARENGOTZ : What was the data threshold voltage shift for the Goddard MOS-FET in that fluence of electrons?

DR. TRAINOR: Less than one volt.

MR. DIVITA: There, again, I might point out, is evidence of parameter importance in the question that Jack Barengoltz asked. Knowing the operational parameters or electrical characteristics have a significant influence on how these parts get rated. I would like to show what the potential problem is relative to our design restraint and what it looks like relative to the best estimate that we have right now. I know there have been other models presented today, and I suspect that probably the other presenters could give me a fluence to be put on the bargraph. Most of the other models fell, I think in the nominal model area. Probably, if you look at any of the models, they would all be in the 10^{10} to 10^{11} range as a nominal model. I don't know about the uncertainties that one would place on all models, but, regardless, it looks like we potentially have a design problem or a test problem.

I might point out there are a number of alternatives we have available that could be used. We are looking into the use of radiation-hardened parts. Radiation-hardened for gammas, rates of prompt gammas, and for a neutron fluence. Also, there may be some kind of an equivalency that can be established between neutrons and protons. If one can identify an equivalent, then it is possible one can replace certain part types with radiation-hardened parts.

DR. MEAD: In order to get fluence, you have to assume some specific mission, don't you?

MR. DIVITA: Yes, we do.

DR. MEAD: Which mission?

MR. DIVITA: The mission we assumed is that we have a flyby that goes through the peak of the Warwick-Divine model, which I believe is located about 0.8 R_J altitude. We used the flyby mission which has 0.8 R_J as an altitude to get the total fluence. That also provides us with a fluence--as identified earlier--which, satisfies that one-tenth R_J altitude mission and any other mission beyond that. I think Jim Trainor pointed out that you pick up maybe an order of magnitude reduction in fluence going in from the 1R_J altitude mission to a 5.6 R_J altitude mission, which is true. If you can go out to, maybe, 7 R_J altitude and have the corresponding upper limit as a design restraint, the restraint decreases another order of magnitude.

MR. BECK: That one-tenth R_J altitude mission was originally designed to be the '76 mission, wasn't it?

MR. DIVITA: That altitude was originally designed to be the '76 mission.

MR. BECK: Just looking at that, it would look like I would have to have three or four orders of magnitude to improve some parts. Do you really expect to get that kind of improvement by going to hardened parts?

MR. DIVITA: Well, I don't think without an evaluation and some testing that you can discuss an equivalence between protons and neutrons. I think you have to do the testing. You have to select some hardened parts and do some measurements in proton fields.

DR. HAFFNER: Van Lint, as you know, has done some studies concerning the equivalence of protons, electrons, gammas, and so on into first approximation. Your protons have an energy which are probably a factor of 1-5 more damaging than neutrons of the same energy. It is routine to harden parts to levels of 10^{12} to 10^{13} neutrons per square centimeter. Admittedly, the neutron energies, correspondingly, are somewhat lower energy than the protons in this restraint, so we would think that,except possibly for your low frequency power transistors which are notoriously weak, as well as some of the unhardened four-level devices, such as silicon-control rectifiers, for this particular mission, you could probably get by with hardened parts. I can't see shielding, but I can see radiation hardening.

MR. DIVITA: In regard to hardening, I know that some of the parts have been hardened to neutron levels to as much as 10^{14} and 10^{15} n/cm^2. Again, I stress that you have to do testing on these devices and identify the parameter, because you anticipate the rating, you have the long-life requirement, and you don't know where you really are on this bargraph for any given part. I am looking at two orders of magnitude spread in Figure 12 for the low-frequency power transistor. If, indeed, you can account for proper identification of the electrical parameter of interest and the derating factor and the operational lifetime of that particular device in its use you would know about the problems. I am saying that you don't know where you really fall on the bargraphs until you do the tests.

DR. BARENGOLTZ: I would like to make a comment about the question about which mission this was, because, unfortunately, I showed my graph that showed the mission dependence earlier. If the nominal model or the best-estimate model applied, that is for a mission with a periapsis less than 2 R_J. If you went to a periapsis of about 6 R_J, you can drop a couple orders of magnitude very easily and get down to where only some power transistors are in trouble.

MR. DIVITA: In summary, there is still a lot of work to do, and it doesn't mean that you necessarily have to do this with hardened parts. I think a couple of people have mentioned that you don't have all your missions flying through the peak of the belts.

MR. BECK: This paper closes the session dealing with current Jupiter radiation belt models and with radiation effects on the TOPS spacecraft. The upper limit models predict fluences of electrons and protons which are quite severe in terms of effects on spacecraft components and science instruments. To design to the severe models requires that a penalty be paid either by excluding certain components or science instruments, employing radiation shielding, or assuming a greater mission risk. The questions before this group then are what are the best nominal trapped electron and proton models for the Jupiter radiation belts for spacecraft design and what are the lowest upper bounds that can be placed on the electron and proton populations. The answers to these questions constitutes the work before us for the next two days.

INFORMATION FROM JUPITER'S DECAMETRIC RADIATION

Thomas D. Carr*

I am supposed to discuss whatever information can be extracted from Jupiter's decameter-wavelength bursts regarding particles possessing MeV energies which might damage a passing space vehicle. Now this is a rather large order, because the decametric emission mechanism is not yet known. Furthermore, it is most likely that the electrons which generate the radio emission have energies in the keV rather than the MeV range, energies which are sufficiently low that there would be no serious threat to spacecraft systems survival. On the other hand, the decametric radiation <u>has</u> provided us with an amazing complex of clues relating to Jupiter's magnetospheric environment. When we are able to interpret them correctly, and to fit them in with the information obtained at decimeter wavelengths, we will be well on the way toward a detailed quantitative understanding of many of the interrelated processes at work in the Jovian magnetosphere. Unfortunately, it is not likely that a definitive theory of Jupiter's magnetosphere will have evolved in time to aid the designers of the presently proposed outer planets spacecraft. Almost certainly, such a theory will not be forthcoming until after space vehicles have thoroughly explored Jupiter. Meanwhile, however, environmental factors which must be considered in the design of the craft will have to be evaluated on the basis of data and theories which are either already available or can be produced in the very near future. I regret that I cannot deduce from the decametric data the high energy particle fluxes in Jupiter's radiation belts, which is the thing we would most like to know. But I will discuss some recent decametric results, as well as some which are not so recent, which may have at least an indirect bearing on the subject under consideration here.

I shall start with a brief review of certain of the outstanding characteristics of the Jovian decametric phenomena. The radiation has been observed from about 40 MHz down to the lowest frequencies capable of penetrating the terrestrial ionosphere. Its occurrence probability depends

*University of Florida, Gainesville, Florida 32601

jointly on the central meridian longitude of Jupiter and the orbital position of the satellite Io. Figure 1 demonstrates this relationship. It is based on observations made at the University of Florida at 18 MHz during the apparition of 1968-69. Three central meridian longitude regions of increased occurrence probability are apparent. These are designated as Sources A, B, and C. They may not actually represent different source regions on the planet, but are probably distinct emission beams which rotate with it. Alternative designations which are often used instead of Sources B, A, and C are the early, main, and late sources, respectively. As can be seen from the slide, the occurrence of emission in the B and C longitude regions is highly dependent on the phase of Io. That from the A region is not, although there is often an Io-related component of A. The Io phases for B and C emission are about 90° and 240°, respectively, from superior geocentric conjunction. The System III rotation period, on which the central meridian longitudes are based, is the value which appeared at the time of its selection to keep the radio source regions most nearly at the same longitudes year after year.

Periods of burst activity are called noise storms, and are usually well defined except at the lower frequencies. The frequency band occupied by a storm usually drifts slowly up or down the spectrum, changing its width as it goes. Figure 2 shows characteristic drifts for Io-related Source B storms. This plot was derived from two of the many beautiful dynamic spectrograms which have been obtained by Warwick and Dulk (Dulk 1965). The drift patterns are more or less repeatable for given runs of central meridian longitude and Io phase. A noteworthy feature of these and other types of Jovian decametric observations is that the emission is never found above 39.5 MHz, the level indicated by the dashed line in the slide.

There are many other interesting decametric effects which could undoubtedly provide us with new information on Jupiter's magnetosphere if we were able to interpret them, as for example, the polarization phenomena, the millisecond and microsecond pulses, and a veritable hierarchy of types of frequency drifts. I cannot dwell on these effects, but I would like to mention that there are pulses with durations of only 20 microseconds (Flagg and Carr 1967) which display frequency drifts, either upward or downward, at the

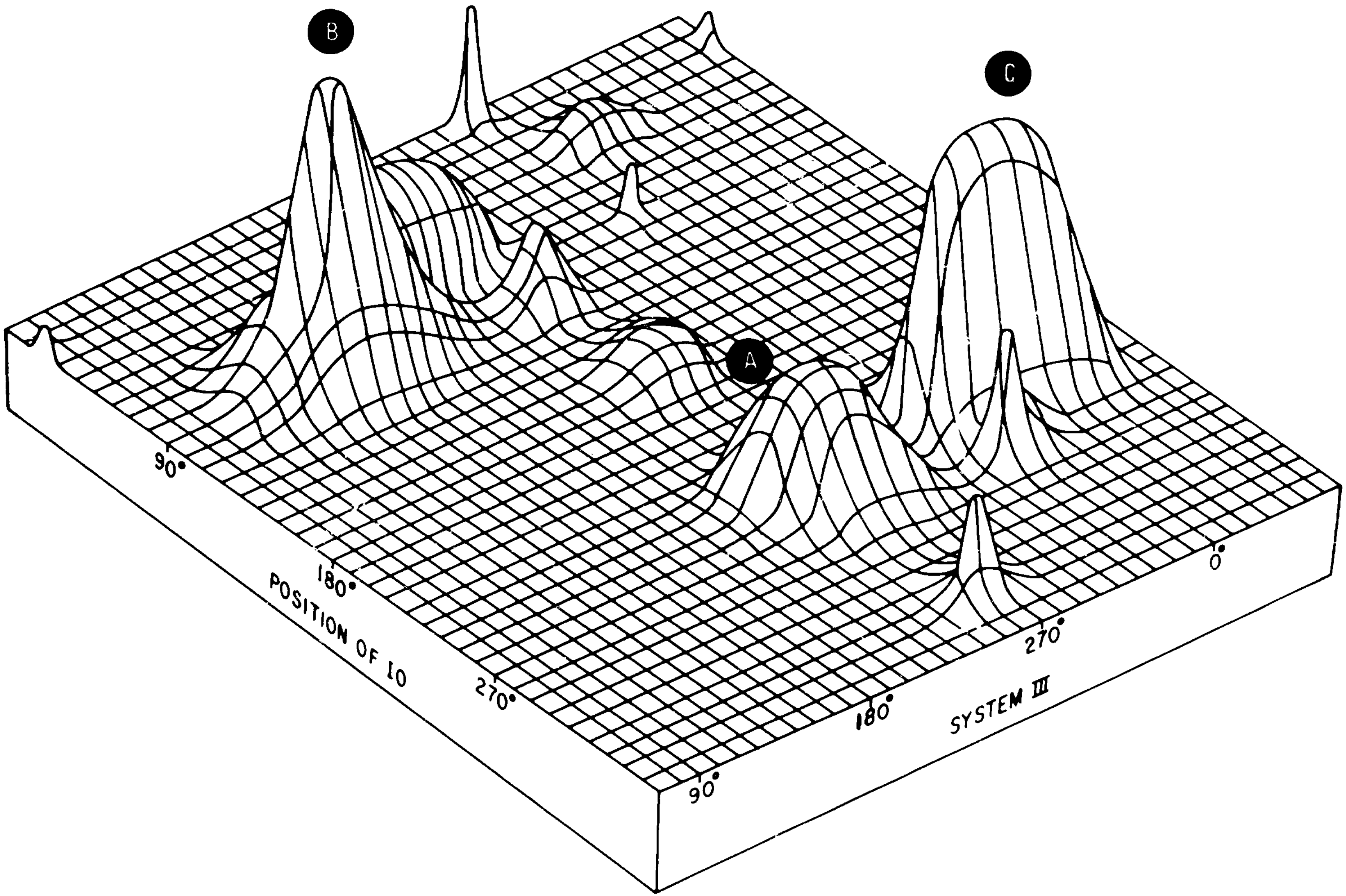

Figure 1. Probability of Occurence of 18 MHz Radiation from Jupiter -- plotted as a function of both the System III longitude of the central meridian and the phase of Io relative to superior geocentric conjunction. The observations were made at the University of Florida Radio Observatory during the apparition of 1968-69.

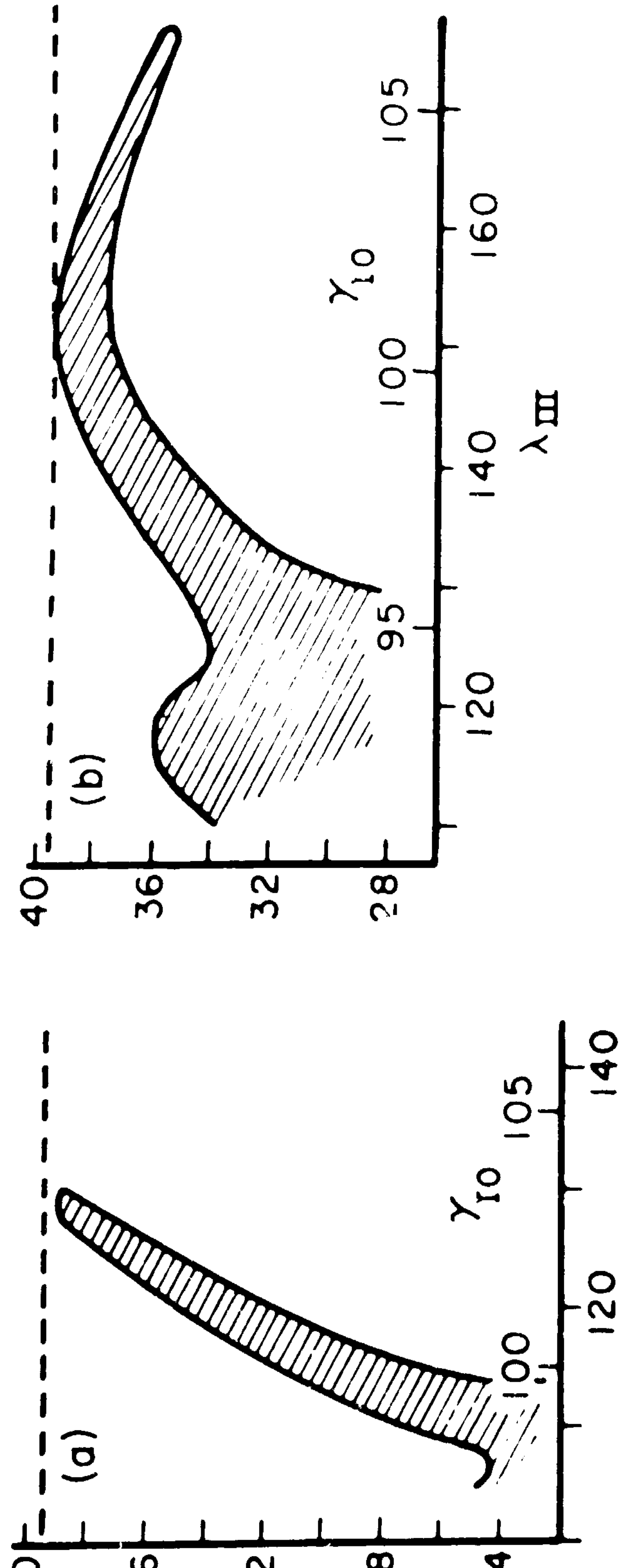

Figure 2. Examples of Source B (Early Source) Frequency Drifts (after Dulk, 1965)

incredible rate of 1000 MHz/sec (Lebo et al. 1971). The storms as a whole and the various types of bursts or pulses that make up a storm exhibit at least four distinct categories of frequency drifts, ranging from 10^{-3} to 10^{+3} MHz/sec. The complexity of Jupiter's decametric radiation is undoubtedly a reflection of the complexity of its magnetosphere.

I would like to mention briefly the use of decametric data to estimate Jupiter's surface magnetic field strength, which is a key parameter in any theory predicting energetic particle fluxes. The most often quoted estimate for the surface field is approximately 14 gauss, based on the decametric data. The line of reasoning in deducing this value is that the decametric radiation is emitted in the extraordinary mode close to the local electron gyrofrequency, and that the highest observed frequency is emitted where the field is strongest. The maximum frequency of 39.5 MHz would thus correspond to a maximum field strength, in the emitting region, of 14 gauss. It is usually assumed that the emitting region extends relatively close to the planetary surface, in which event the surface field strength would indeed be approximately 14 gauss. Although this may well be the case, it is not necessarily so. For example, the possibility that the emission originates from the vicinity of Io has not yet been ruled out. Let us assume for the moment that the frequency of maximum emission, which appears to be in the vicinity of 10 MHz, is the electron gyrofrequency at Io's orbit. The corresponding magnetic field at this location would be 3.6 gauss, or about 800 gauss at the surface of the planet. This is not so far from the minimum surface field of 1000 gauss recently suggested by Kemp et al. (1971) to account for their observation of a circularly polarized component of the light from Jupiter. If such a powerful Jovian field really exists, which seems rather unlikely, we might expect that the decametric radiation consists of an electron gyrofrequency component from the vicinity of Io combined with a proton gyrofrequency component from near the planetary surface. My point is that we should keep in mind that the surface field of 14 gauss obtained from decametric measurements should be considered a lower limit, and not lose sight of the fact that the actual field might possibly turn out to be much stronger.

I will now discuss some old and new results related to the beaming of the decametric radiation. It has long been supposed that the effects illustrated in Figures 1 and 2 are due to the rotation with the planetary magnetic field of a complex set of emission beams. The shapes and orientations of these beams are probably controlled in some way by magnetospheric structure, perhaps including the influence of pronounced magnetic field anomalies. Figure 3 shows a beam structure proposed by Dulk (1967) [and by Piddington and Drake (1968), with elaborations by Goldreich and Lynden-Bell (1969) and by Schatten and Ness (1971)] which seems to go a long way toward explaining the geometry of the control exercised by Io. The radiation is beamed within a thin conical sheet where the flux tube passing through Io meets the top of the ionosphere. Source B is seen when this sheet first crosses the direction of the Earth, and Source C when the other side of the cone sweeps past. Goldreich and Lynden-Bell show that their proposed coherent cyclotron emission mechanism gives rise to a cone of the proper opening angle to account for the relative longitudes of the two source regions. With the further assumption of east-west beaming within the conical sheet and the consideration of the drag on the flux tube by Jupiter's ionosphere, the Goldreich and Lynden-Bell theory also predicts the correct phases for Io during emission. Although Dulk and the other authors imply that both Sources A and C arise from the same side of this emission cone, I propose that most of the Source A emission is associated with a quite different type of beam, which I shall discuss next.

The general level of Jupiter's decametric activity exhibits a slow variation having a period on the order of a decade. This effect has appeared to be more or less in anticorrelation with the smoothed sunspot number, and for a long time the relationship was believed to be a real one. However, Carr et al. (1970) presented evidence which supported to some degree the idea that the activity variation is simply a beaming effect brought about by the slight variation in the direction of the Earth during the course of Jupiter's 11.9 year orbit about the sun. This direction angle is called the Jovicentric declination of the Earth, abbreviated D_E. It is the altitude angle of the Earth above or below the plane of Jupiter's equator. Its range of variation is from about -3.3 degrees to +3.3 degrees. Since the periods of the variations in the sunspot number and D_E differ by only about 10 percent

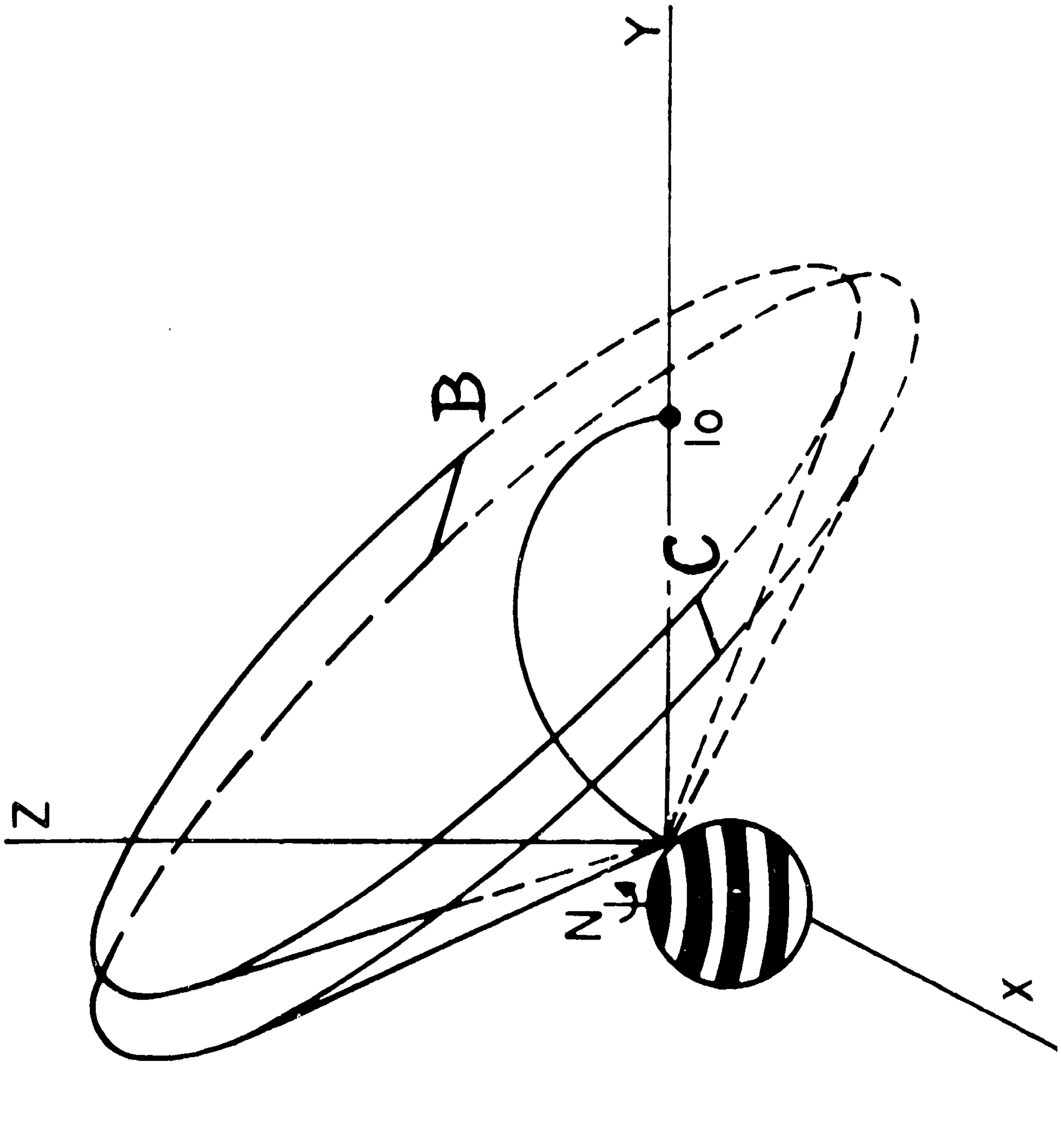

Figure 3. Emission Beam Structure -- proposed by Dulk and others (after Dulk, 1967)

and the two have been nearly in antiphase for over a decade, it is very difficult to discern which is actually influencing the reception of Jupiter's radiation. However, the observations obtained at the University of Florida Radio Observatory now span 14 consecutive apparitions of Jupiter, and I believe a clear picture is beginning to emerge. Figure 4 shows 14 histograms of occurrence probability at a frequency of 18 MHz as a function of central meridian longitude, one for each apparition. The rotation period used in reckoning central meridian longitude is the one advocated by Carr (1971); its value is 9 hr 55 min 29.75 sec. Source A is approximately in the middle of each histogram. The pattern of variation in the total Source A activity is striking. There was maximum Source A activity during the apparition of 1963.8, and almost none for 1958.2 and 1970.2. Both the sunspot minimum and the D_E maximum occurred about 1964.8, a year after maximum Source A activity. The 1958.2 Source A minimum nearly coincided with both the sunspot maximum and the D_E minimum. But I think it is significant that the recent disappearance of Source A coincided with the D_E minimum, while it occurred a year after the sunspot maximum. The total Source A activity per apparition was plotted against both sunspot number and D_E; it displayed a more consistent relationship with D_E than with sunspot number. Perhaps the most convincing evidence that the true relationship is with D_E is shown in Figure 5. Here the central meridian longitudes of the minima preceding and following the Source A maximum are plotted as a function of D_E. Least squares straight lines were fitted to the two sets of points. It is seen that the position of the leading null varies little with D_E, but that of the trailing null does markedly. It thus appears that the variation in the width of Source A, and hence of its total activity, results from changes in the angle D_E. This implies a Source A emission beam having the cross section indicated at the top of the slide. The beam cross section must also extend above +3.3 degrees and below -3.3 degrees, but we do not have the opportunity to explore these regions because of the limited range of D_E. Such an asymmetrical beam also accounts for the observed 11.9 year periodic drift in the position of the center of Source A (Carr et al. 1970).

In summary, it appears that Sources B and C result from the two sides of a bi-lobed beam, while the Source A beam is quite distinct and

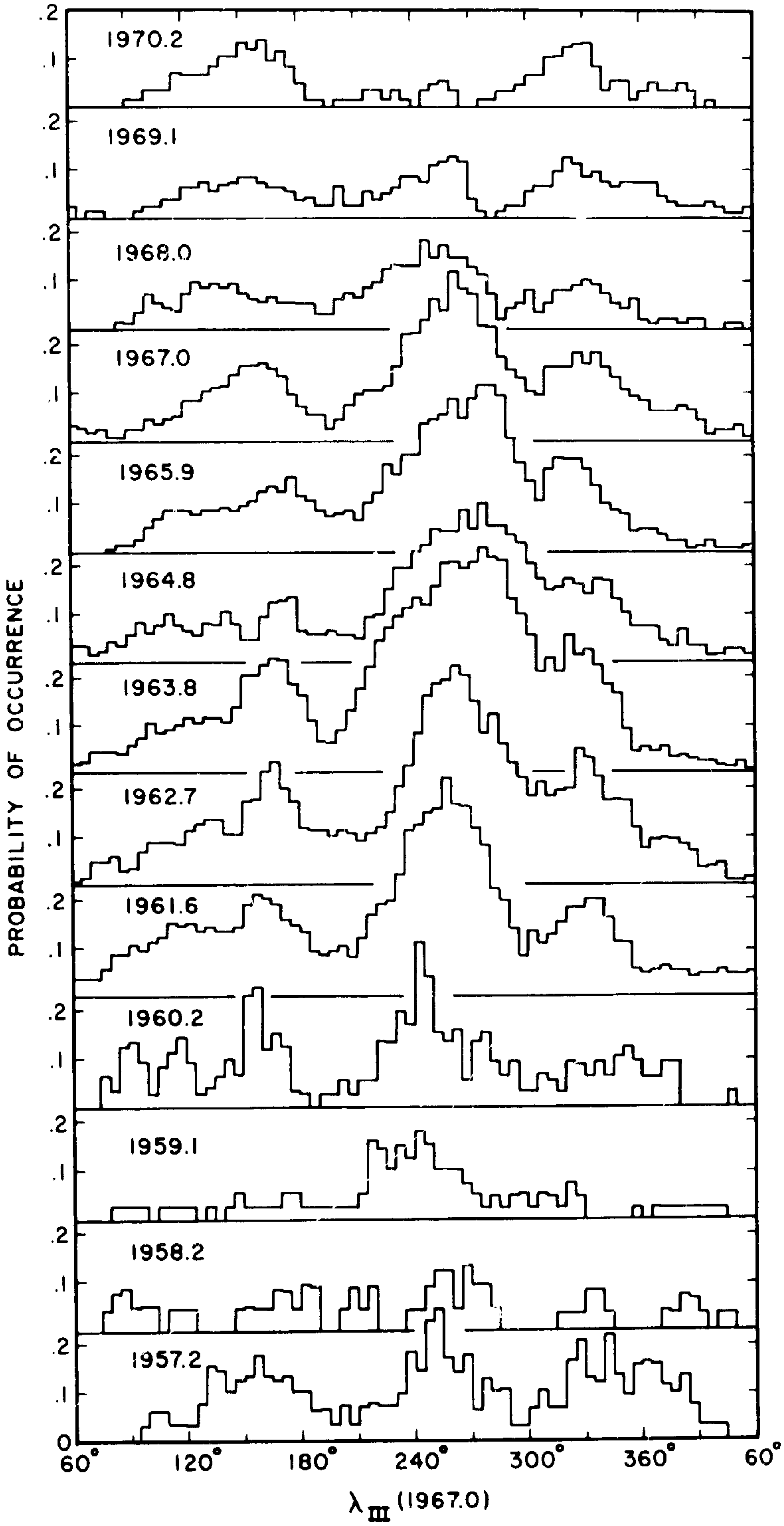

Figure 4. Histograms of Occurrence Probability -- as a function of the revised System III longitude of the central meridian for 14 consecutive apparitions. The observations were made at the University of Florida Radio Observatory at a frequency of 18 MHz.

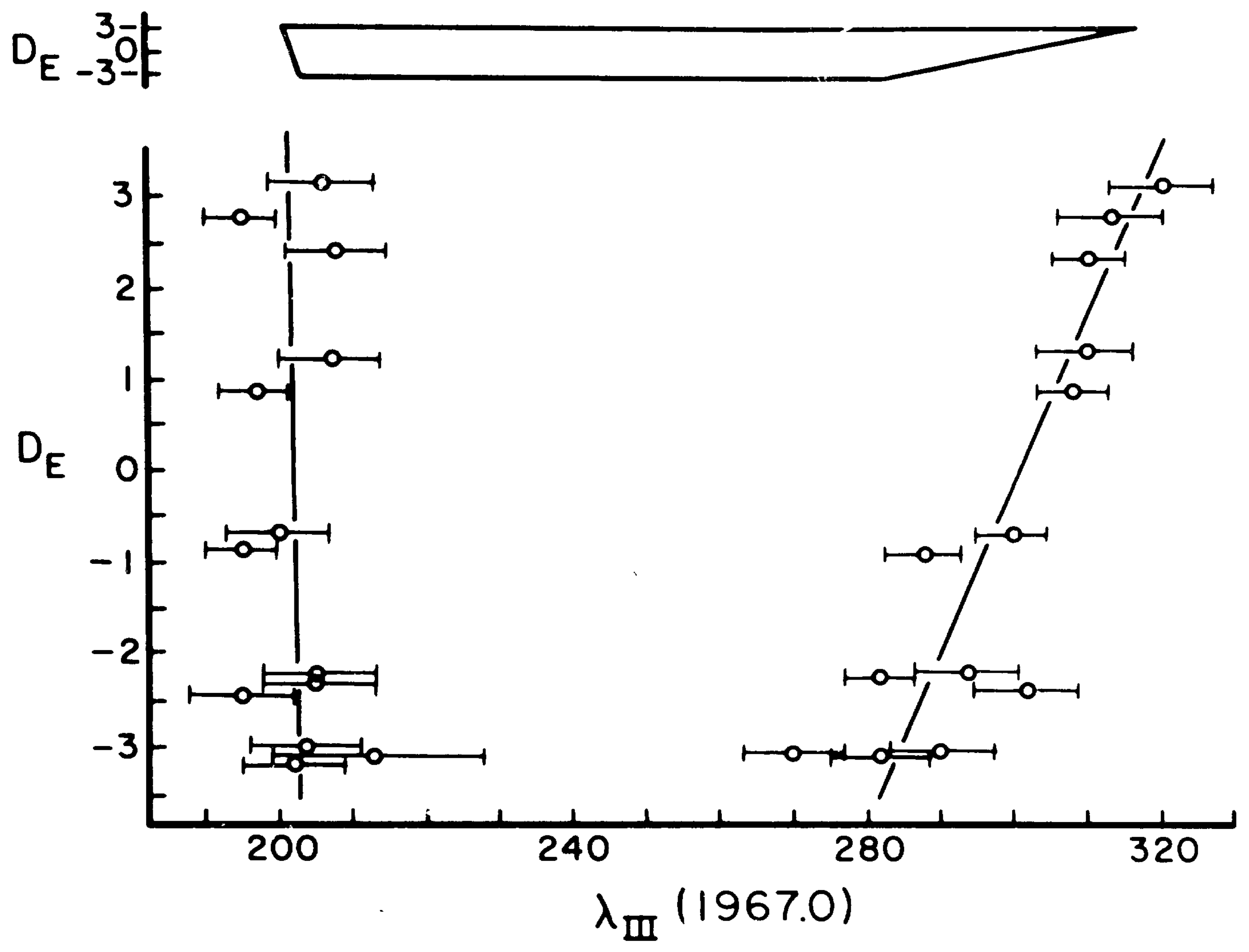

Figure 5. The Central Meridian Longitudes -- of the minima proceding (left) and following (right) the Source A maximum, plotted as a function of D_E. The figure at the top is a scale drawing of the cross section of the postulated emission beam.

has a different shape. The B-C beam is excited whenever Io crosses the meridian toward which Jupiter's northern hemisphere pole is tipped, but is of such a shape that changes in D_E have no observable effect on reception. On the other hand, the A beam is much more nearly independent of Io, but is so shaped that the small changes in D_E produce large effects. Perhaps these generalities can be translated into features or characteristics of Jupiter's magnetosphere, the knowledge of which would be of benefit in our search for new information on the radiation belts.

Before concluding, I would like to call attention to a pair of recently published papers which are apparently in conflict regarding the location of Jupiter's plasmapause, an important structural feature of the magnetosphere. The plasmapause lies at the boundary of the plasmasphere, within which plasma escape into interplanetary space is prevented by always-closed magnetic field lines. Outside the plasmaphere the plasma is depleted because escape is possible along field lines which open into interplanetary space as they transit the magnetospheric tail. Brice and Ioannidis (1970) show that Jupiter's plasmapause probably lies relatively close to the magnetospheric boundary, which is at least 50 planetary radii from the surface on the sunward side. On the other hand, Conseil, Leblanc, Antonini, and Quemada (1971) have discovered an effect which leads them to believe that a portion of the plasmapause lies within Io's orbit, located at a distance of 6 planetary radii. They have observed a rather convincing correlation between the rate of change of solar wind velocity at Jupiter, as extrapolated from Earth satellite measurements, and the phase of Io during Source C decametric noise storms. They propose a model in which Source B emission is induced by the passage of Io into a bulging plasmasphere, and that from Source C as Io emerges from it. They maintain that the location of the plasmapause, and hence, the phase of Io at the times of decametric emission, are strongly influenced by the solar wind velocity. Although their explanation does not seem probable in the light of the theoretical work of Brice and Ioannidis the effect they have discovered is none the less interesting. It is the most convincing evidence so far presented that the solar wind does exert a measureable influence upon Jupiter's decametric radiation. If such an effect could be definitely established, there would be important implications with regard to magnetospheric theory.

Finally, there is that item of unfinished business regarding the decametric Faraday effect which must be settled. Warwick (1967) interpreted the failure to detect any sort of Faraday effect which could be attributed to Jupiter's magnetosphere as evidence that the electron density must be less than 10 per cm at a distance of 1 radius from the surface. In the review paper by Carr and Gulkis (1969), a statement was made to the effect that it is not clear that this conclusion necessarily follows. Our line of reasoning was that radiation emitted in the extraordinary mode near the local electron gyrofrequency will remain in that mode as it propagates out through the magnetosphere provided there is no pronounced discontinuity along the path, and that if the conjugate mode is absent, there can be no Faraday effect. It is most important in the context of this meeting to rectify the difference between Warwick's interpretation and ours. Our statement may very well not have been justified; a brief discussion this morning should settle the matter.

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DISCUSSION

DR. LIEMOHN: The relationship to D_E that you assumed is the zenographic equator tilt with respect to the position of Earth; is that correct?

DR. CARR: That is the tilt of the Earth with respect to Jupiter's true rotational equator.

DR. LIEMOHN: Has anything been done to compare this with the tilted dipole?

DR. CARR: It is undoubtedly tied in with the dipole tilt. The beam, if there is a beam, is probably fixed with respect to Jupiter's magnetic equator, and that's what causes this effect.

DR. WARWICK: The longitude plots are uniquely related to magnetic declination, and there is a 1 to 1 computation that you could make to convert them to that coordinate range. The reason that that is possible is that the rotation period Tom has used is accurately the rotation period of the magnetic field.

DR. LIEMOHN: If you included that map, would it bring these curves more into alignment?

DR. MEAD: D_E has a unique value for any apparition with respect to geographic area, but there is no unique value for D_E magnetically, plus or minus 14 to something like that.

DR. WARWICK: Plus 13 to minus 7, for example.

DR. LIEMOHN: But the curves are for a particular short two- or three-month epoch probably, and if you were to hold that effectively, I wonder if there were anything that might sort out the data a little more.

DR. CARR: I would say most of those are for almost a year. We were observing continuously all the way around the year, although most of the data did come from a three-month interval.

DR. BRICE: I am not at all surprised that the solar wind has an influence, but it is not the plasmapause. I will probably discuss that this afternoon. I think that in the paper that was referred to on the plasmapause is one that we have available. We have a subsequent one in our Icarus article discussing the plasma density. There are set conclusions from that which impact the conclusions of the first one so that we now have to rehash our magnetosphere model.

DR. CARR: The plasmapause is still way out.

DR. BRICE: I don't think there is a plasmapause anymore.

DR. MEAD: I would like to make a comment on the 14 gauss magnetic field strength. Of course, with the dipole field there is always a factor of 2 between the equator and the pole. Therefore, when you say the field is 14 gauss from the surface,that is wherever this radiation is, which is a rather high latitude. When we in the radiation belt talk about a surface field, we usually try to normalize it to the equator. That would be about 8 to 10 gauss at the equator.

DR. WARWICK: I have one point to make, which shouldn't be regarded as a hard comment on what Tom (Carr) has said, but I think there is another implicit assumption that seems to be made very wisely, and it was imbodied in the graph that Tom showed of my colleague, George Dulk's model of the Io relationship. That is that the decametric emission relates to the foot print of Io's flux in Jupiter's ionosphere. I think that is still an assumption. If I may advance a personal opinion whichis not a demonstrated fact, I believe that that is probably not the re on of decametric emission. It may be from another point of view a probable so ce point of the emission, but in that case we cannot conclude from the magnetic latitude of the foot print that the decametric emission occurs at high magnitude latit es. It may well occur at low magnetic latitudes.

DR. BRICE: We have been working a little bit on the problem of decametric radiation. If you map the magnetic field around Io to the ionosphere, you get an ellipse which is very elongated. The major to minor axis has a ratio of about 10. We believe that the beaming is essentially two dimensions. One is a plane of constant magnetic field, and the other one is the direction of the major axis of this ellipse.

DR. WARWICK: But that may not be the source of emission. I think that the emphasis in the literature has been entirely on the flux tube of Io, as evidenced by Goldreich and Lynden-Bell's model, for example, and Shatten and Ness, and so on, but I don't think that is a proven case.

DR. MEAD: Do you have, Jim[1], a mechanism in mind that would put it at a different latitude?

DR. WARWICK: Yes. It is talked about in NASA CR-1685*.

DR. LIEMOHN: I would just like to mention that several years ago I made some calculations on the cyclotron radiation and the Cerenkov radiation from electrons in the magnetoplasma, and I found that both modes radiated energy. The mode I called the extraordinary one radiated significantly more than the ordinary or whistler mode, and the amount of radiation that came off was stronger above the electron-cyclotron frequency than below--not much above, but still around that frequency.

DR. CARR: Both modes are emitted.

DR. BRICE: That is just way too low, Harold[2]. That is just too inefficient a mechanism. What we propose is the amplitude that you see that represents a quasi-stable situation similar to what you have in the whistlers on Earth, except that the amplification is now waves propagating at right angles to the beam of electrons coming from Io. Amplification is the way to propagate through that beam and then a very small amount of reflection at the edge of that beam.

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[1] Dr. Warwick

[2] Dr. Liemohn

*Warwick, J. W., "Particles and Fields Near Jupiter," NASA CR-1685, 1970.

DR. LIEMOHN: What you are doing is invoking a new mechanism of amplification.

DR. BRICE: We are invoking a plasma instability with a small amount of reflection so that you can use the growth rate several times. In order to get a high enough efficiency into the radiation, I think the efficiency you need is something like one percent, perhaps a little more. That is, one percent of the kinetic energy of the particles has to go into radiation. It is very difficult to get that high of an efficiency unless you have some mechanism that gets close to a quasi-stable status.

DR. LIEMOHN: I will admit that it probably requires a coherent mechanism, but I will question the availability of a bouncing amplification process because of what I am going to say to you tomorrow. It is based on your model.

DR. GULKIS: The question that we have to answer is whether or not the limiting polarization can be elliptical and have a high density. The observations are that the polarization of the wave turns out to be elliptical. Now, if the electron density falls off very, very slowly, then the limiting polarization will turn out to be circular.

DR. CARR: It doesn't really come out circular for all directions of propagation except transverse.

DR. GULKIS: The axial ratios typically are half for most of the bursts.

DR. CARR: I mean theoretically.

DR. BRICE: I think so, because the electron density is likely to be extremely small, perhaps 0.1 cm^{-3}. That means that you go very rapidly from transition, say, where you are below the cyclotron frequency to above the hybrid frequency. Where those transitions take place in, say, a few kilometers or less in a very small distance, then the refractive index for the waves is going to change very rapidly as a function of distance. That is likely to give you mode coupling so that you are likely, then, I think, because of this effect to get two modes out, even though you may only have one mode going in.

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SOME RECENT OBSERVATIONS AND INTERPRETATIONS OF THE JUPITER DECIMETER EMISSION*

Glenn L. Berge**

INTRODUCTION

I shall discuss four distinct topics relating to the decimeter radio emission of Jupiter. These particular topics were chosen for their relevance to the Jupiter Workshop. The discussion relies, to some extent, on new and unpublished data and, to some extent, on new interpretations or analyses of older data.

The decimeter emission we observe from Jupiter consists partly of thermal radiation from the planetary disk (presumably from Jupiter's atmosphere) and partly of nonthermal radiation from a region of larger angular extent. The latter is thought to result from synchrotron emission by relativistic electrons in Jupiter's magnetic field. The two contributions are about equal at a wavelength of 7 cm. At longer wavelengths, the nonthermal part remains roughly constant in flux density while the thermal part falls off approximately as one divided by wavelength squared.

The integrated nonthermal emission is polarized with a degree of linear polarization of about 20 percent and E-vector parallel to the magnetic equator. The E-vector varies by ±10° as Jupiter rotates, implying that the magnetic axis and rotation axis differ in direction by about that amount.

Comparison of Maps at Different Wavelengths

Two maps have been published which give detailed brightness contours for the decimeter emission. The first (Berge, 1966) at epoch 1963.8, was at a wavelength of 10.4 cm. It was obtained by fitting parameters in a generalized, two-dimensional, geometric model to interferometric data. The range of

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** *Owens Valley Radio Observatory, California Institute of Technology, Pasadena, California 91109.*

central meridian longitudes was divided into four 90-degree segments and the published map represented the segment centered at λ_{III} = 20°. The second (Branson, 1968) at epoch 1967.2, was at a wavelength of 21.3 cm. In this case, there were three 120° segments, and all three maps were presented. They were obtained by direct Fourier inversion of interferometric data.

There are several approaches that one can try to unfold two-dimensional maps to estimate the volume emissivity at different places within the radiation belt. Then, for certain types of assumed electron energy distributions, one can use the volume emissivities, their ratios at different wavelengths, and an assumed magnetic field intensity to find the density and characteristic energy of the relativistic electrons as functions of position in the emitting region. This is what Beard and Luthey have been doing as reported at this workshop.

However, one must be very careful in comparing the two maps mentioned above and in interpreting the comparison because the maps represent rather different things. There are three essential differences:

(1) The 10.4 cm data were first used to solve for the thermal disk temperature. Then the thermal contribution (T_D = 260°K) was subtracted so that the contour map shows only the nonthermal emission. The 21.3 cm maps, however, include the thermal disk contribution.

(2) The maps include the effect of smoothing by the instrumental angular response (synthesized beam) and these were much different at the two wavelengths. The 21.3 cm maps have slightly better east-west resolution, but much poorer north-south resolution, than the 10.4 cm map.

(3) The 10.4 cm map represents the total intensity (Stokes parameter I obtained from the sum of two orthogonal polarizations). The 21.3 cm maps show only the response to one polarization (E-vector east-west). In terms of Stokes parameters, they represent (I + Q) approximately, where the reference axis is taken along the magnetic equator.

Since Q varies through the range $-I \lesssim Q \lesssim I$ over the source, it is clear that this is a serious effect.

To compare the maps properly, it is necessary to convert them to similar form. This is usually accomplished by converting to the "lowest common denominator." For example, one cannot improve the angular resolution of an existing map, but one can smooth out a higher resolution map to make it comparable.

The 21.3 cm maps were made at a time when Jupiter's rotational axis was only 12° from celestial north-south. The maps show essentially no resolution of Jupiter in the polar direction because of the large north-south extent of the synthesized beam. That is, the half-power width of the maps in the polar direction is not significantly larger than the half-power width of the beam. Thus, there is no particular loss of information in considering an equatorial strip scan in which the emission is integrated in the polar direction. This is what I shall do because it is less confusing.

The 21.3 cm maps do not themselves contain enough information to convert to the Stokes parameter I. However, the 10.4 cm data contain the polarization information, and it is possible to convert to a map showing what one would see with the polarization response used for the 21.3 cm maps.

Figure 1 shows the relevant strip scans for half of the source. The upper dashed curve is the 21.3 cm scan that was obtained by Branson for the map at λ_{III} = 255°, except that the east half has been folded over on the west half and averaged with it. Branson estimated a disk temperature of 250°K at this wavelength, and a uniform disk of this temperature, as smoothed by the beam, has been removed from the scan. The upper solid curve is the corresponding 10.4 cm scan with a disk of 260°K removed. It was obtained by interpolating between the models for λ_{III} = 200° and λ_{III} = 290°. (For comparison, the lower solid curve is what one sees with the opposite plane of polarization.) The 10.4 cm and 21.3 cm scans have been drawn so their maxima are of equal height in order to compare their shape, but there is a separate scale, in absolute units, for each of them.

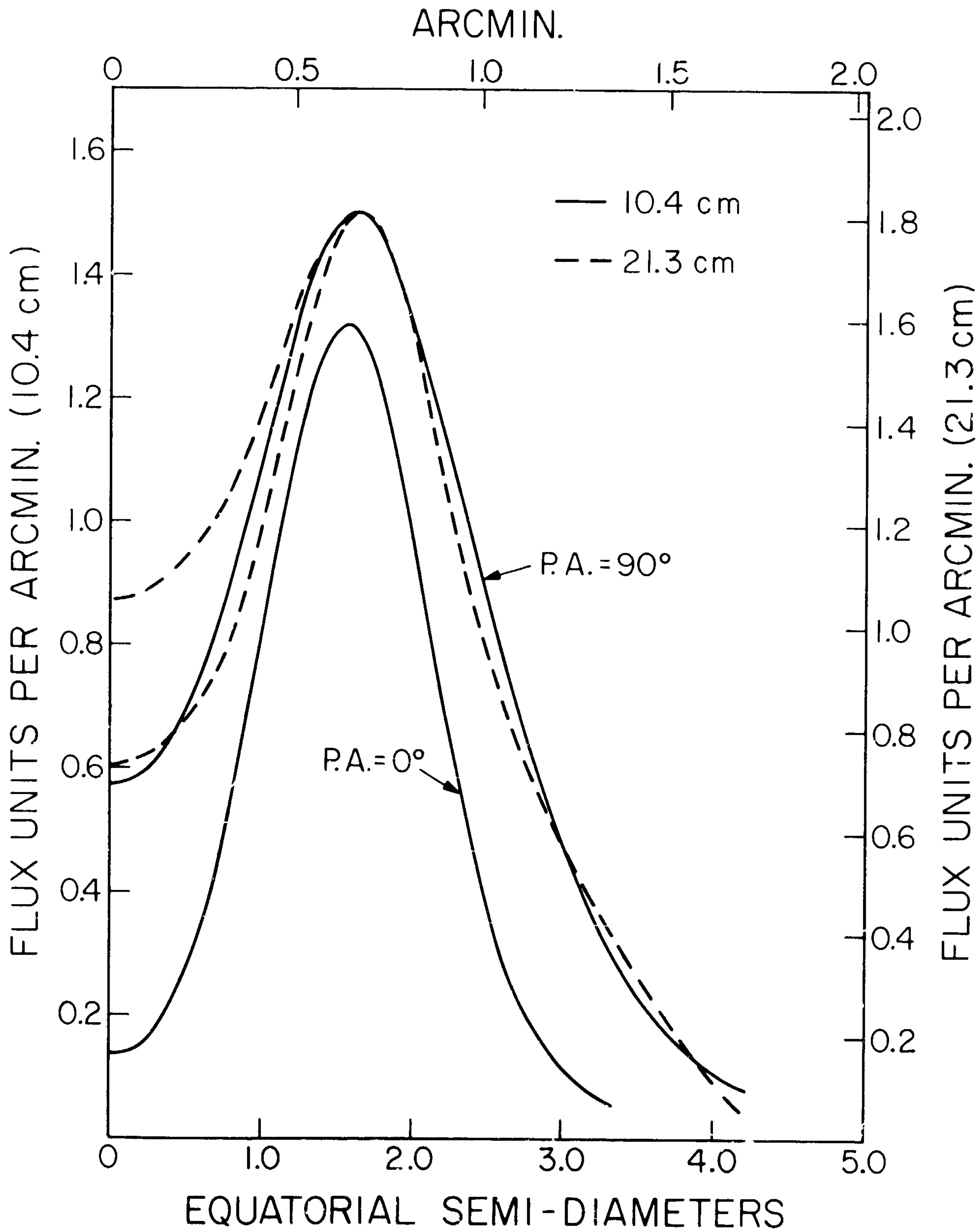

Figure 1. Equatorial Strip Scans

NOTE

Figure 1 shows equatorial strip scans at 10.4 and 21.3 cm outwards from the center. The emission has been integrated in the polar direction so the units are flux density per unit angle. The dashed curves represent the 21.3 cm emission with a 250°K disk removed (upper curve) and a 450°K disk removed (lower curve) as seen by an instrument which is linearly polarized with the E-vector at position angle 90° (east-west). The solid curves represent the 10.4 cm emission with a 260°K disk removed as seen with the instrumental E-vector at P.A. = 90° and at P.A. = 0°. The instrumental factor of 1/2, which people usually ignore, has been included in the vertical scales. That is, the total at 10.4 cm is the sum of the two curves rather than their average. The vertical scales and top scale are for a Jupiter-Earth distance of 4.04 AU.

Figure 2, following, shows the longitude plane which contains the measured centroid of the total emission at 21.1 cm. The units given are equatorial semi-diameters. As shown, the greatest displacement toward celestial east occurs when the System III central meridian longitude (epoch 1969) is at 138°.

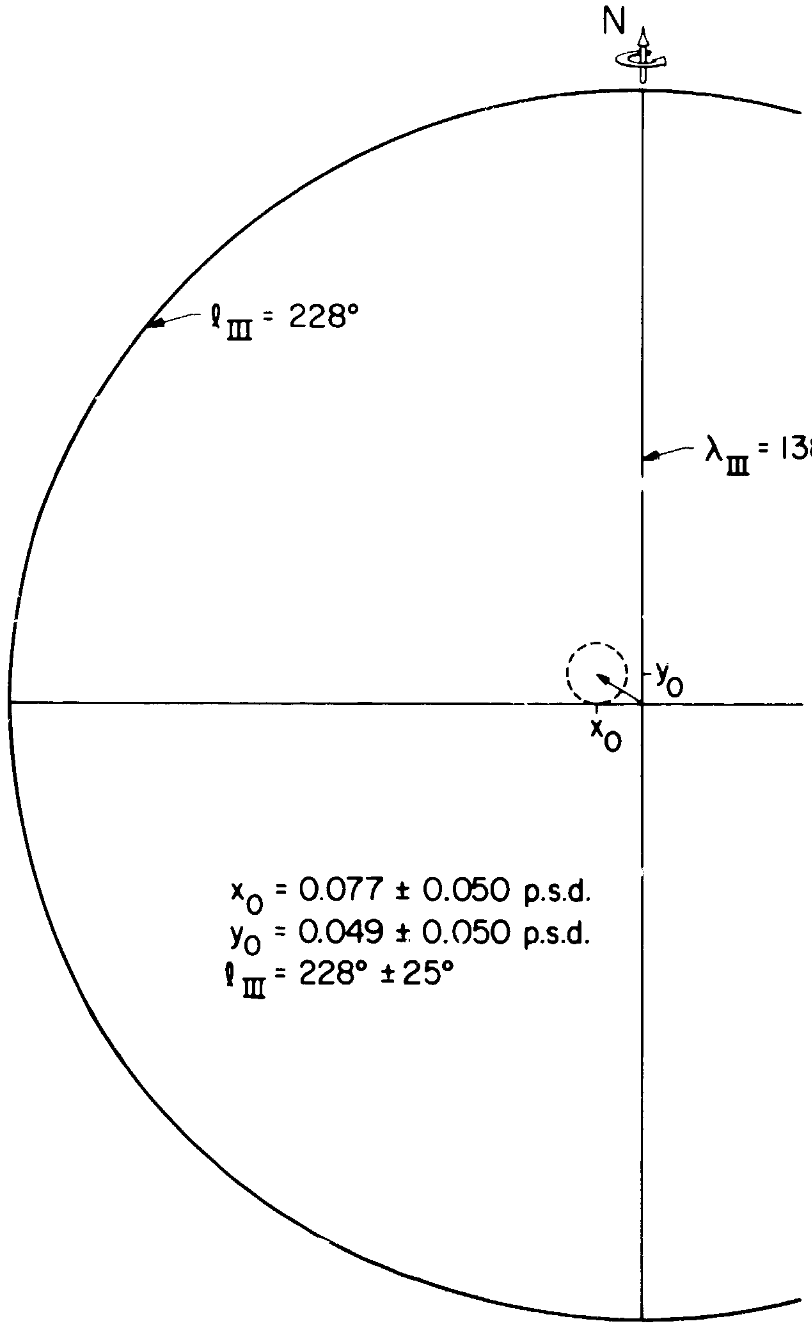

Figure 2. 21 cm Emission Centroid Position*

*Refer to "Note" following Figure 1.

The two frequencies agree quite well in shape except in the inner regions where the thermal disk contribution is uncertain. One would expect T_D (21.3 cm) > T_D (10.4 cm) for the thermal part because the longer wavelength is further out in the wing of the ammonia absorption spectrum. The lower dashed curve is what one obtains at 21.3 cm after removing a disk of 450°K instead of 250°K. Such a temperature is consistent with the value of $T_D = 400 \pm 75$°K obtained by Berge (1968) from an independent analysis of Branson's maps.

With the higher temperature for the disk at 21.3 cm, the scans of the nonthermal emission are remarkably similar in shape at the two frequencies. The 21.3 cm peak is slightly narrower, but this can be explained by the superior east-west resolution at this wavelength. (No attempt was made to broaden the 21.3 cm strip scan.) The conclusion is that the scans are consistent with the ratio of the volume emissivities being constant ($J_{21}/J_{10} \approx 1.2$) throughout the emitting region. However, there is not enough information to prove that this is the case.

Centroid Position of the 21 cm Emission

Jupiter was observed at 21.1 cm in April, 1968 and May, 1970, using the interferometer at the Owens Valley Radio Observatory with various short baselines. The position angle of Jupiter's axis was 22° east of north. One piece of information obtained was the centroid position. The baselines were short enough to keep from resolving the source appreciably, but long enough to yield useful position information. Each measurement of the interference phase represents a measurement of the position in one dimension (along the direction of the projected baseline) at one particular longitude of the central meridian. 361 such measurements were obtained with various projected baselines and at various longitudes. These were used to solve for a "best-fit" centroid fixed in the polar direction and varying sinusoidally with LCM in the equatorial direction. Such behavior assumes that the emission centroid is fixed in Jupiter and rotates with it and that beaming and shadowing have little effect on the apparent position.

The results are shown in Figure 2. The position of the disk center, to which the measured position is referenced, was taken to be the ephemeris position after correcting for parallax. The small measured displacement does not itself yield a unique model for the magnetic field, but it does seem to rule out a magnetic field displacement of several tenths of a radius as suggested by Warwick (1963, 1970). The magnetic field appears to be quite well centered and reasonably symmetric.

The measured displacement, when compared to its uncertainty, does not represent a formal detection of a displacement, but it is of interest to note that its longitude coincides, within the uncertainty, with the longitude towards which the north magnetic pole is tilted and also with the longitude of the "hot spot" which exists in the maps of Branson (1968). The equatorial component of the displacement is in good agreement with the periodic variation which appears in the right ascension measurement of Roberts and Ekers (1966). These measurements, made in November, 1964, when the position angle of Jupiter's equator was 75°, imply an equatorial displacement of 0.07 equatorial semidiameters in the longitude plane 220°.

Circular Polarization and the Magnetic Field Intensity

Several detections of circular polarization of Jupiter's decimeter radio emission have been published (Berge, 1965; Seaquist, 1969; Komesaroff, Morris, and Roberts, 1970). Circular polarization measurements were also made during the observing runs mentioned above, the 1970 measurements being the more accurate. A sinusoid can be fitted to the fractional circular polarization (V/I, where positive is right-hand and negative is left-hand) as a function of longitude of the central meridian (λ_{III}) to yield

$$V/I = (0.004 \pm 0.002) - (0.010 \pm 0.002) \cos (\lambda_{III} - 212° \pm 11°) \quad (1)$$

for epoch 1970.4. The magnetic latitude of the Earth, as seen from Jupiter at the same epoch is given by

$$\Phi_M = -\left[(3.1°) - (10° \pm 1°) \cos (\lambda_{III} - 218° \pm 3°)\right]. \quad (2)$$

Komesaroff et al. (1970) have also measured the circular polarization at 21 cm with a different instrument and different technique. They obtained

$$V/I = (-0.0019 \pm 0.0011) - (0.0111 \pm 0.0016) \cos (\lambda_{III} - 206° \pm 6.9°) \qquad (3)$$

for epoch 1967.0. At that time, the magnetic latitude was

$$\phi_M = -[(-0.8°) - (10° \pm 1°) \cos (\lambda_{III} - 207° \pm 3°)] \quad . \qquad (4)$$

The expected correlation between V/I and ϕ_M is very good in each case. Furthermore, the agreement between the two sets of measurements, after allowing for the change in ϕ_M, is excellent. Thus, the chance of large unknown systematic errors seems remote, and one's confidence in the results is improved. The relative sense of V/I and ϕ_M is what yields the sense of the magnetic moment. The magnetic pole in the northern hemisphere is a north magnetic pole in agreement with Warwick (1963).

In principle, the circular polarization can be used to estimate the magnetic field strength in the source. A simplified explanation, which is not revealed in an obvious way by the usual formulae, is that the circular polarization allows one to calculate the width of the synchrotron emission cones of the electrons. This gives the electron energy which, in turn, gives the field strength. In practice, however, it is necessary to know the electron energy distribution and pitch angle distribution and the way in which the circular polarization is distributed across the source in order to convert from circular polarization to field strength. Uncertainties in our knowledge of these things leads to a large uncertainty in the answer.

Komesaroff et al. (1970) assumed a power law energy distribution and the pitch angle distribution given by Thorne (1965). The distribution over the source was handled by using thin-shell model calculations which have been integrated over the source to compare with the integrated polarization measurements. They find that the equatorial magnetic field at 3 radii from the center of Jupiter is between 0.4 and 1.9 Gauss. I agree with these limits, but I think that they apply, more realistically, to 2 radii from the center. This would give a surface equatorial field between 3.2 and 15.2 Gauss. The precision is poor, but it is gratifying that the result is consistent with estimates made from the decameter emission. Furthermore, the result gives additional evidence that the decameter emission arises not very far from the surface.

Faraday Rotation and the Density of Thermal Electrons

An upper limit on the Faraday rotation of the decimeter emission can be used to set an upper limit on the density of thermal electrons surrounding Jupiter just as Warwick has done with the decameter emission (Warwick, 1970). The resulting limit is poorer at higher frequencies, but there is no uncertainty about the type of propagation and Faraday rotation. One expects quasi-longitudinal propagation and Faraday rotation.

The Faraday rotation of the plane of polarization should depend on Φ_M and should be zero when $\Phi_M = 0$ (for a spherically symetric magnetic field and electron density distribution). As Jupiter rotates, the Faraday rotation will vary in a roughly simisoidal fashion with longitude. This variation will be 90 degrees out of phase with the variation in E-vector position angle caused by the rocking of the magnetic equator. The observed position angle variation will be the sum of these. When Faraday rotation is added to the normal rocking, the amplitude will increase, the phase will change, and, unless $D_E = 0$, the base level will change. There will also be complex depolarization effects. All of these effects will be greater at longer wavelengths because of the wavelength-squared dependence of the Faraday rotation.

Some years ago, I estimated that the plane of polarization would be rotated about 10° at 21 cm when Φ_M is maximum if there is a uniform electron density of 10^4 cm^{-3} throughout the source (Berge, 1966). This seemed like a very conservative estimate of what could be there without being detected.

This limit can be improved by using more recent data and by considering the change in phase of the position angle variation. It can be shown that, for a uniform density, this change in phase is given approximately by

$$\alpha = -\tan^{-1} (2.3 \times 10^{-8} K n_e B_E \lambda^2) \qquad (5)$$

where: K is a constant of order unity

n_e is the electron density in cm^{-3}

B_E is the surface equatorial field in gauss

λ is the wavelength in cm.

K depends on the geometry of the field, the variation in field strength throughout the radio source, and the distribution of emission throughout the source. A rough analysis shows that $1/2 \lesssim K \lesssim 2$, but with more effort, it could be calculated more accurately. For a nonuniform density distribution of assumed form, the added effect could be included in K, and n_e would take on the character of a scale factor. K would then not necessarily lie in the range given above.

The data currently available indicate that $\alpha < 10°$. This results from comparing the phase of the 21 cm position angle variation with that measured at shorter wavelengths where the effect is much smaller and also from comparison with the phase of the well-known beaming effect. Using this number we find that $n_e < 2 \times 10^3$ cm^{-3} for $B_E = 8$ gauss and $K = 1$ or $B_E = 16$ gauss and $K = 1/2$. This limit rules out the possibility of very high densities such as suggested by Gledhill (1967). It is a poor limit compared to current theoretical estimates, but it helps rule out gross flaws in the assumptions used. Furthermore, the limit can be improved by measurements at longer wavelengths. It appears feasible to obtain a similar accuracy for α at 100 cm wavelength if the data are corrected for ionospheric Faraday rotation by using information obtained from observations of stationary satellites. Such observations are made routinely, and the information is available. Then the upper limit on n_e could be reduced to about 100 cm^{-3}.

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DISCUSSION

DR. BRICE: What is the number you come up with for the surface equatorial field?

DR. BERGE: Well, let me quote the latest result from Parks in which they analyze their data. At 3 radii they determine a field of 0.4 to 1.7 gauss. I have a slight disagreement with the location, but I would agree with those figures at 2 radii from the center. Thus, the equatorial field would be eight times that.

DR. BEARD: I just recently tried to make an inverse Fourier transform of your published visibility curves for the east-west polarization, and I get the same thing that you did with a much better graph and much better data. The effect of this can be seen in our source intensity per cubic centimeter. We get a curve beyond the maxima of both Branson at 21 centimeters and your result at 10.4 centimeters. We get a source intensity that is completely parallel to Branson's, within any possible experimental distribution, all the way out to 4 or 4-1/4 Jupiter radii. The effect of this on the analysis that Luthey and I made is that the energy of the electrons (the electron temperature) is surprisingly constant all the way out, whereas the temperature contour on our model falls off as R^{-3}.

DR. BERGE: I think there are potential dangers in comparing different types of maps, and I think there is a danger in assuming that you can obtain a very high resolution scan along the equator just by reading off contours.

DR. BEARD: I fold in the resolution of the antenna and take that into account when I solve for the source intensity.

DR. BERGE: What I am saying is that in Branson's maps, there is not enough information to solve for a high resolution equatorial cut, as if he had had a smaller beam. For example, his contours in the equatorial plane are diluted by radiation coming from higher magnetic latitudes, which has different polarization and different structure parallel to the equator and all sorts of complications.

DR. WARWICK: In your latest study of the brightness distribution centroid, you mentioned that you assumed that the north-south centroid was fixed. I wondered if you did that because the data suggested it to you, or is it possible to sort out the north-south data according to longitude of the central meridian and solve for a possible variation in that direction? As I said yesterday, it seems to me probable, even, that there is a north-south oscillation in the position of the source, be it of unknown amplitude, to be sure.

DR. BERGE: If there is a polar-direction oscillation, it will show up as part of the east-west oscillation, as the source was tilted in the sky.

DR. WARWICK: Right. I am simply asking whether it is possible to analyze for oscillations along the rotation direction as well as in the equatorial plane of the rotation, or did that come out automatically in your data?

DR. BERGE: No, it did not. It is a more complicated problem, and I don't know if you could get a realistic separation of the two effects.

DR. WARWICK: On the basis of the preprint you sent me, I made a rough estimate. It would seem to me likely that a swing-through, ± 5 or 10 percent of a radius in a north-south direction, should occur no matter what the centroid of the dipole is. Even for a centered dipole, there should still be an oscillation up and down.

DR. BERGE: The main defect in my assumptions was that I assumed no shading by the planet.

DR. WARWICK: And I assume the shading to predict that there is a north-south oscillation.

DR. BERGE: That's right.

DR. WARWICK: But I don't know that there is one, and you might be able to determine it. I guess that's what I am saying.

DR. BERGE: I just have the impression that it would be hard to do, and I didn't try it.

DR. MEAD: Of course, the longitude system is the originally defined λ_{III}. Therefore, you have to state a time. You gave a date, didn't you?

DR. BERGE: Right. The epoch is about the middle of 69. That is, I have two series of observations spaced by two years. Over this two-year period, the whole system will slip by 6 degrees or so, and that isn't very serious compared to the error I had on the longitude.

DR. LUTHEY: Branson used a synthesized pencil beam on his 21 centimeter data. Is it possible for him to get better resolution in the equatorial plane for east-west polarization because of this pencil beam they used?

DR. BERGE: Well, his pencil beam was drawn in the upper left-hand corner of his maps, and that represents the resolution anywhere in the source.

DR. HESS: What are the chances in the next couple of years of getting better resolution maps?

DR. BERGE: Well, the potential is very good. I don't know about the chances regarding the people who are interested in doing it. I would certainly like to do it at some other wavelength, myself. It is easier now to get maps like this.

DR. WARWICK: Is Al Sinclair's group (that used the NRAO interferometer) going to publish their work? Do you have any readout on that?

DR. BERGE: I don't know. The last I heard was that they weren't sure that they had enough information to get maps. That is, you need a lot of information, because you have to separate it according to longitudes. They didn't know if they could get resolution sufficient to avoid smearing with longitude. You should be able to get maps of some sort.

DR. WARWICK: I have diagrams in a preprint form, and I suspect you do, as well, from their work, but I have been nervously awaiting what would appear in print.

DR. BERGE: Well, their group sort of broke up, and I don't know what their plans are for the data.

DR. BEARD: What wavelength was used?

DR. WARWICK: Eleven to twelve centimeters.

DR. DAVIS: In view of the fact that the energetic electron content of the Jupiter radiation belts is clearly very important in the problem of design of a spacecraft to go near Jupiter, would it be sensible or would it not be sensible to try to organize within the next couple of years some kind of a coordinated program which would make measurements of the kind which can be made today? The purpose from the beginning would be to perform the kind of analysis that Beard and Luthey have done but without some of the peculiar intermediate steps in which you look at observations, prepare a synthesis of them, and then decompose the synthesis and put it back together in another way. That is, one starts from the observations and goes as directly as possible to the answer. Perhaps the group could come to some opinion as to whether this is a good idea.

DR. BERGE: I certainly think that this general method is potentially very useful and your comment about trying to make maps which are uniform in their characteristics is, I think, the most important part. One would like to use the same instrument to make maps at several different frequencies because available interferometers are much, much different from one another. The problem is that at each wavelength, one needs different baselines measured in feet to get equivalent resolution. For example, an instrument that could do it at 50 centimeters probably couldn't get short enough spacings, even, to do it at 5 centimeters. There are various practical problems. Another problem is that most suitable instruments are in the northern hemisphere, and Jupiter is far south now, which means that north-south resolution is difficult to achieve.

DR. BRICE: I have begun some preliminary discussions with the Mills Cross people about observing Jupiter at something like 70 centimeters, and I don't know whether that will bear fruit or not. Their primary instrument has a beam width which is of the order of 10 planetary radii, so you would need a secondary instrument off on the side some distance away to do interferometric studies. They are interested in doing it if someone is interested in coming down there to do it with them.

I think it is extremely important to determine what the electrons are, because it is highly probable, in my view, that the energy in the protons is very closely related to that in the electrons. If we have a good understanding of what the electron energy densities are, then we will have a good understanding of what the protons are.

DR. THORNE: You mentioned there seems to be a 10-degree inclination between the geomagnetic and geographic equatorial planes. Is it possible to put firmer limits on that angle?

DR. BERGE: Firmer than what? I didn't put any limits on it.

DR. THORNE: Could you put limits on it from the synchrotron emission? Would it be greater than 5 degrees or less than 20 degrees?

DR. BERGE: Well, all of the observations indicate something very close to 10 degrees, or between 9 and 10 degrees, with errors of 1.5 degrees, or something like that, except that Warwick has proposed an angle which is slightly less than my lower limit.

DR. WARWICK: Why don't you put Jim Roberts' slide* back on, and I will show you what the point was. The upper curve shows the polarization position angle as a function of Jupiter longitude. The point that Glenn is making is that the semiamplitude of that curve is 10 degrees with an error on the order of a degree or so. The point I am making is that the semiamplitude of that curve does not uniquely define the inclination of a tilted dipole to the rotation axis. There are at least two other parameters of the curve that could be used

* Fig. 2(c) from Roberts, J.A., and Komesaroff, M.M., 1965, Icarus 4, 127.

to define an inclination. One of them is the rate of change of position angle at one of the crossovers. The other parameter is the rate of change of position angle at the other crossover. The semiamplitude is of the order of magnitude of 10 or maybe 11 degrees with an uncertainty which is measured by the spread in the points. That is one way of estimating the inclination, and it is clearly of the order of the magnitude of 10 degrees. Another way to get it is from the rate of change of position angle on the ascending part of the curve at the left-hand side. A third way to get it is from the rate of change of the position angle on the descending part of the curve in the center. As you can see, those latter two methods won't agree with one another. In fact, the one on the left-hand side of the slide gives a tilt which is less than the semiamplitude. The one in the middle gives a tilt which is greater than the semiamplitude, so there are three different values. They are respectively 8, 10, and 12 degrees. You have to have a basis for choosing between those. I propose a basis, which I won't repeat now, which was that the left-hand one was the appropriate one to choose.

DR. MEAD: Perhaps I could point out that when you take the rate of change, you are differentiating the points. Anybody knows in working with data that differentiating gives you much greater errors, whereas integrating normally gives you greater reliability.

DR. WARWICK: Excuse me, but we are not differentiating. What we are doing is taking all the points between 45 degrees on that curve and about the second division in. We are totaling those together, and we are getting the slope of the curve. If you do the problem as a problem in statistics, you will find that the error on that slope, when converted into position angle or tilt angle, yields an error of the order of less than 1 degree. To put it another way, there is a significant statistical difference between the slope on the left and in the center.

DR. MEAD: I think that could be some nonuniform or nondipolar aspect of the basic field which might lead to some nonsinusoidal dependence. Intuitively, I feel that the amplitude of the curve seems to be more directly related to the tilt of the primary dipole term.

DR. WARWICK: Well, if you could convert your intuition into a hard logic, I would accept that. I tried to go through that intuition, and hard logic led me to the left-hand one. Incidentally, I will say what the logic is. A decentered dipole in the north-south sense, if it is shifted into the southern hemisphere, explains the difference between those two as a result of a shadowing effect. It turns out to be the same shift that I concluded for decametric sources before these curves were even made. That is why this whole decentering problem is an extremely nervous one for me. I simply don't know how that kind of curve can be produced without planetary scale inhomogeneities. We are not talking about a small effect. We are talking about something integrated over the entire radiation belt and systematic with the rotation of the planet through 360 degrees. I don't claim to understand why Berge gets that result, and I am certainly not saying that it is wrong. It is an obviously beautiful result on the precise centroid of decimetric emission, but how are you going to understand that top curve? I don't think that the amplitude is the way that you are going to understand, and, yet, I see problems remaining in the explanations that I have offered.

DR. BERGE: I might mention, getting back to the question of the 8 degrees or 10 degrees or whatever, the high resolution maps themselves offer another way of determining this number. In fact, Branson's maps at different longitudes give you some handle on it, although they are hard to use to get a very accurate number, as his beam is so noncircular that the map distorts as the major axis tilts.

DR. BRICE: Is it your point that when the dipole is tilted towards you or away from you, you get less shadowing of the radiation from behind the planet than when it is tilted in the east-west way?

DR. WARWICK: Yes. There is an asymmetry in the shadowing when the dipole is tilted towards you as compared to when it is tilted away. That is what produces the different rate of change in the slope. It just turned out to be consistent with the southward displacement. Several other people and I have followed that logic through, and it appears to be all right so far.

DR. THORNE: The reason I was asking the question was, while it is interesting to know whether it is 8 or 12 degrees, I am more concerned with the problem of the penetration of particles from the solar wind to the inner regions of the radiation belts. If you do have a 10-degree inclination between the two equatorial planes, I think you can get quite appreciable diffusion in.

DR. WARWICK: Is there a difference between 8 degrees and 10 degrees. Intuitively, I would not expect it.

DR. KENNEL: The difference could be made up for with the error in our knowledge of the pitch angles, which is slightly flatter at 8 degrees.

DR. THORNE: I think with 10 degrees, an appreciable portion of the radiation belt fluxes could diffuse.

A NOTE ON THE GLEDHILL MODEL OF THE MAGNETOSPHERE OF JUPITER*

S. Gulkis**

The density of the thermal plasma in the Jovian Magnetosphere is poorly known. Estimates of the density at several Jovian radii range from a maximum of 10^9 electrons/cm^3 (Gledhill, 1967) to a minimum of 1 electron/cm^3 (Brice, 1968). Models with intermediate values of the density have been suggested by Ellis (1965), Melrose (1967), Warwick (1967), and others. With the exception of data obtained by Warwick and his co-workers, experimental data have thus far been of little help in deciding among the various models. Warwick and Dulk (1964), Warwick (1964), and Parker, Dulk, and Warwick (1969) measured Faraday rotation in Jupiter's decametric burst radiation but they find that the observed rotation occurs almost entirely in the terrestrial ionosphere. The absence of Faraday rotation at Jupiter implies that the radiation either is generated above Jupiter's plasmapause or remains in one magnetoionic mode until above the plasmapause. The inferred magnetospheric electron density is less than 10 cm^{-3} if two modes are present.

The model with the highest density is due to Gledhill (1967). He calculates the maximum plasma density in Jupiter's magnetosphere that can corotate with the planet. Although no reasonable arguments have been given as to how this extensively ionized region is formed and maintained against recombination, the model has not positively been ruled out on experimental grounds. The purpose of this note is to point out that free-free emission from the Gledhill model exceeds the flux measured from the planet over the entire microwave spectrum. Consequently, the electron density must be considerably less than Gledhill assumed. The upper limit to the electron density which can be

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** *Jet Propulsion Laboratory, Pasadena, California 91103*

set by comparing free-free emission with the observed spectrum is $\sim 10^7$ electrons/cm^3 (assuming that it is distributed over several Jovian radii).

A simple calculation rules out the Gledhill model and also demonstrates this upper limit estimate. Consider the free-free emission from a constant density, isothermal rectangular slab of thickness $2R_J$ ($1R_J \approx$ 70,000 km) and side dimensions $2R_J \times 8R_J$, as shown in Figure 1 superimposed on the Gledhill model. Note that the plasma density in the Gledhill model is greater than 10^7 electrons/cm^3 throughout the slab (with the exception of the corners). Hence, the radiation from the uniform slab, taken to have a density of 10^7 electrons/cm^3 and a temperature of 1800°K, is a lower limit to the total radiation from the Gledhill model. The flux density that would be observed from this slab is given by

$$S = \frac{2kT}{\lambda^2}\left[1 - e^{-\tau}\right]\Omega \qquad (1)$$

where τ is the optical depth, Ω is the solid angle subtended by the slab, k is Boltzmann's constant, T is the isothermal plasma temperature, and λ is the wavelength.

The optical depth τ of the slab can be calculated from the usual formula for diffuse ionized hydrogen (e.g., Shklovsky, 1960, p. 148) and can be shown to be equal to

$$\tau \approx \frac{1.9 \times 10^6}{f^2_{MHz}} \qquad (2)$$

for T = 1800°K, N = 10^7 electrons/cm^3 and slab thickness $2R_J$. In calculating the opacity it was tacitly assumed that the wave frequency is very much greater than the gyrofrequency and that the magnetic field can be ignored. From this expression we immediately see that the slab is optically thick ($\tau > 1$) at frequencies less than 1400 MHz and hence, it radiates like a blackbody of temperature 1800°K. If the density is much greater than 10^7 electrons/cm^3, as it is

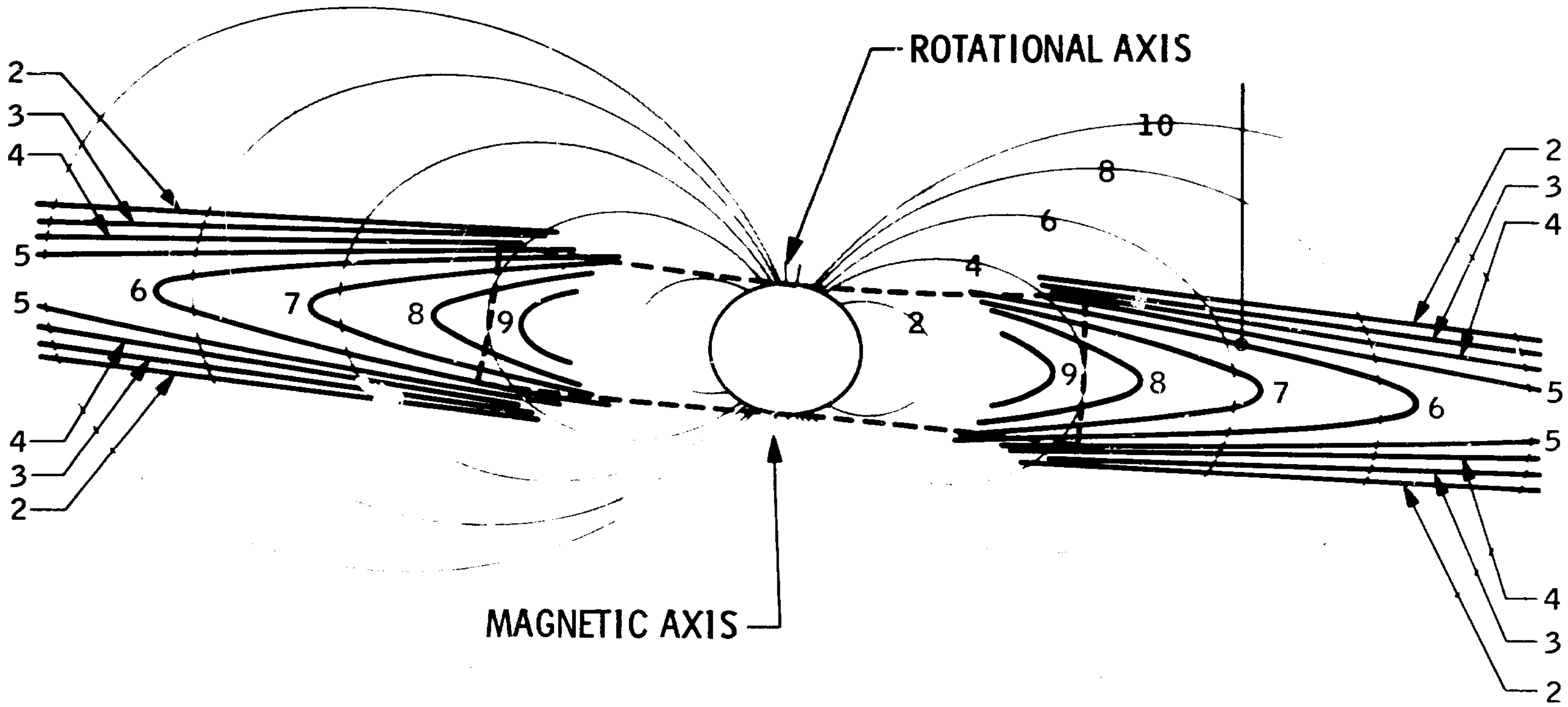

Figure 1. Model of Jupiter's Magnetosphere After Gledhill (1967). B_o = 30 gauss; T = 1800 K. (The numbers on the contours are $\log_{10}$ N where N is the electron number density in cm^{-3}. Outline of $2R_J \times 8R_J$ rectangular slab is shown by the dashed lines.)

in the Gledhill model, the slab would become optically thick at a much higher frequency than 1400 MHz since the opacity increases as the square of density.

The flux density spectra for two (slab) models which differ only in their temperatures (1800°K and 180°K) are compared with the observed (Jovian Spectrum) spectrum in Figure 2. The free-free radiation from the 1800°K slab is shown to exceed the observed Jovian Spectrum over the frequency range from 800 MHz to 10,000 MHz. A reduction of the slab temperature by a factor of ten does not remove the difficulty with the model since the optical depth of the slab increases with decreasing temperatures. Hence, the plasma distribution shown in Figure 1 cannot be a physically realistic mode Since the minimum electron density at Io's orbital radius ($5.9R_J$) in the Gledhill model (2×10^7 electron/cm^3) exceeds the upper limit set by the free-free emission, the emission mechanism proposed by Gledhill to explain the occurrence of decameter burst radiation requires that the electron density increase with distance from the planet.

Acknowledgment

I would like to thank M. Klein, G. Berge and B. Gary for reading this note and making helpful comments.

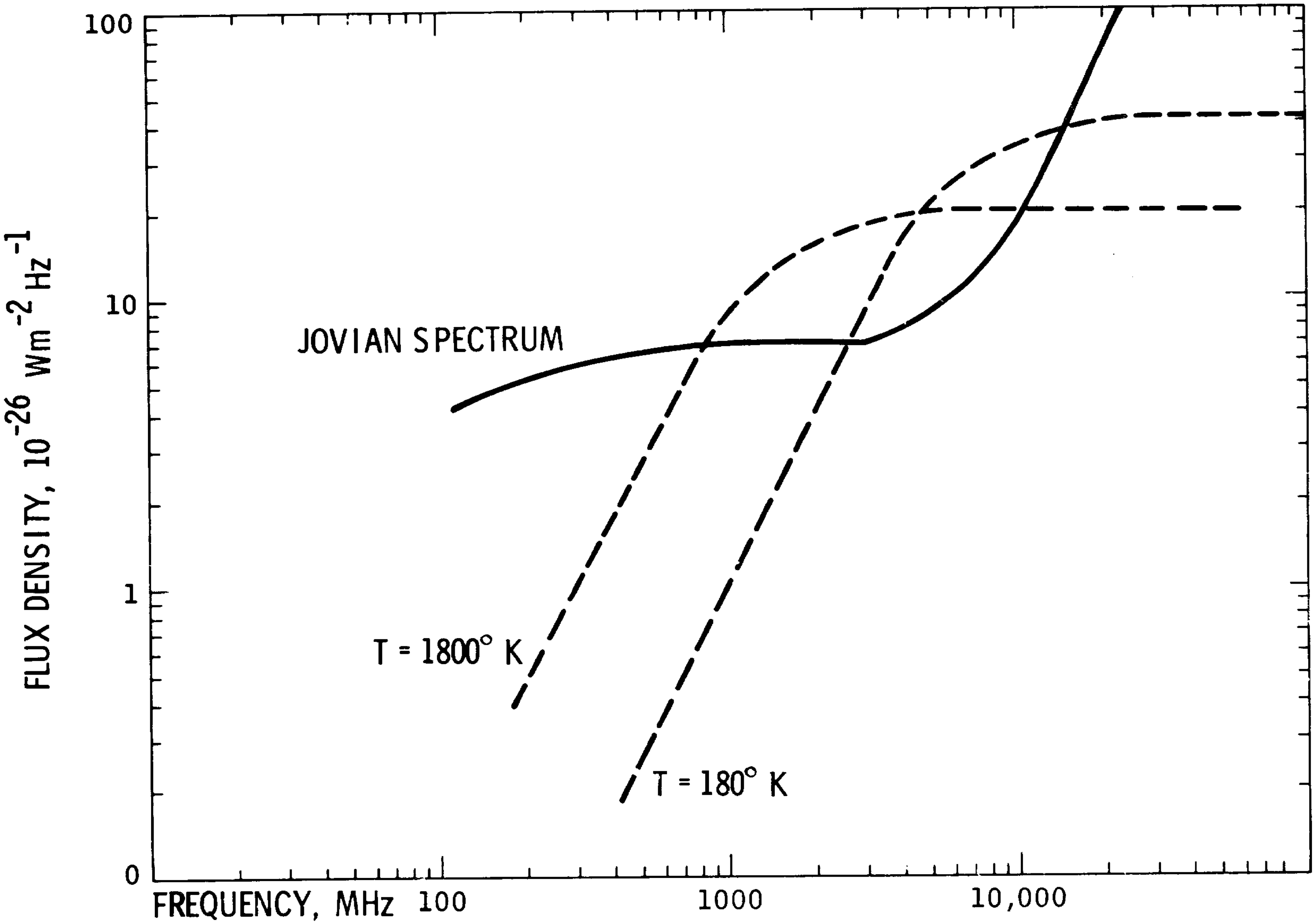

Figure 2. The Observed Jovian Spectrum (e.g., Dickel, Degioanni, and Goodman, 1970) (Jovian Spectrum shown by the solid line. Free-free emission spectra for two models are shown by dashed lines.)

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DISCUSSION

DR. WARWICK: Sam,* may I mention also that H-alpha observations of Jupiter have not detected the source. I think these have been done at the University of Iowa, in fact. The upper limit there is of the same order of magnitude as the one that you just quoted--maybe a factor of 10 less, in fact.

DR. GULKIS: You could probably reduce my estimate by a factor of 10 with a rigorous calculation. My estimate is very conservative.

DR. HESS: You have pretty successfully discarded this matter of 1,000 gauss surface field. I agree with that. Now, the question is can you explain Kemp's optical results**, having gotten around the existence of this kind of a field?

DR. GULKIS: No, I can't. But Kemp himself explained the optical results, and he gave several alternative explanations.

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* *Dr. Gulkis*

** *Comment unrelated to this paper; cf. Kemp et al., 1971,* <u>*Nature*</u> <u>*231*</u>*, 169, and* <u>*232*</u>*, 165.*

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DISCUSSION OF THE RELIABILITY OF ELECTRON DENSITIES AND ENERGIES INTERPRETED FROM DATA AND LIMITS ON THE PROTON ENERGY AND DENSITY*

David B. Beard**

In discussing our theoretical interpretation of radio observations of Jupiter, one thing that is important to keep in mind is that we cannot as yet separate the magnetic field from the electron energy. All that we are able to determine is $\sqrt{H}\,E_0$ where H is the magnetic field and E_0 the electron temperature. We assume a dipole field with a surface equatorial value of 7 gauss and then our values of E_0 follow from this. If you change the magnetic field, then you necessarily change the energy in the results we get.

Also, we have lowered our previous estimates of the energy which means that for a given observed radio intensity our electron densities are raised from our previous estimates (since more energetic electrons radiate more efficiently).

We have changed our analysis to take into account the antenna resolution. As Dr. Luthey described yesterday, we split the equatorial plane up into nineteen concentric rings of widths 0.25 R_J; numbered to start from the outermost ring at 4.5 R_J (labelled one) and numbering to the center of the planet to the ring labelled 19, respectively. We then consider strips 0.25 R_J parallel to the line of sight and perpendicular to the diameter of the rings, and we numbered similarly. The intersection of strip one with concentric ring one, we labeled V_{11}; strip two with ring one, V_{21}; strip two with ring two, V_{22}; etc. Thus, if our antenna resolution were infinitely good, we would have for the flux intensities, S, in the various strips in the forms $S_1' = V_{11}D_1$, $S_2' = V_{21}D_1+V_{22}D_2$, etc.

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**University of Kansas, Lawrence, Kansas 66044; work performed in collaboration with Joe L. Luthey, University of Iowa, Iowa City, Iowa 52240.

where D_i refers to the radiation source intensity per unit volume in ring i.

To take account of the antenna resolution, we employ a sine function or Gaussian function (they are nearly identical) of the separation of a contributing strip from the angular elongation of observation. For example,

$$S_1 = S_1' + S_2' \exp \left| - \alpha\ (2-1)^2 \right| + S_3' \exp \left| - \alpha\ (3-1)^2 \right| + \ . \ . \ .$$

where α is a constant appropriate to the reported antenna resolution of the observer.

In this way we form the equations

$$S(I) = \sum_K FM\ (I,K)\ D(K)$$

and solve them for D(K) in terms of the observed fluxes S(I).

Figure 1 shows our resulting source intensity per unit volume for Branson's observations at 21 cm wavelength. Figure 2 shows our results for Berge's observations at 10.4 cm wavelength. Berge comments in his paper that he has underestimated the flux close to the planet and as you can see we obtained an unacceptable negative source intensity at 1.5 R_J and an unacceptably sharp peak at 2 R_J. For $r > 2\ R_J$, we are fairly confident of the reliability of Berge's reported results, but his data cannot be used in our analysis for $r \leq 2\ R_J$.

Subsequent to the meeting we have improved the analysis further and have obtained better data from Dr. Berge who has been most helpful in discussing his and Branson's observations with us. We have included the geometrical shadowing by the planet of volumes behind the planet and have taken into account the effect of pitch angle distributions and have obtained the results shown in Figure 3. We have also "massaged" the data--raised it, lowered it, added or subtracted background, and tilted it to estimate what effect possible experimental error might have. We are still working on this but as you can see from the figure, we have improved the reliability of the interpretation and have obtained a temperature for the planetary disc.

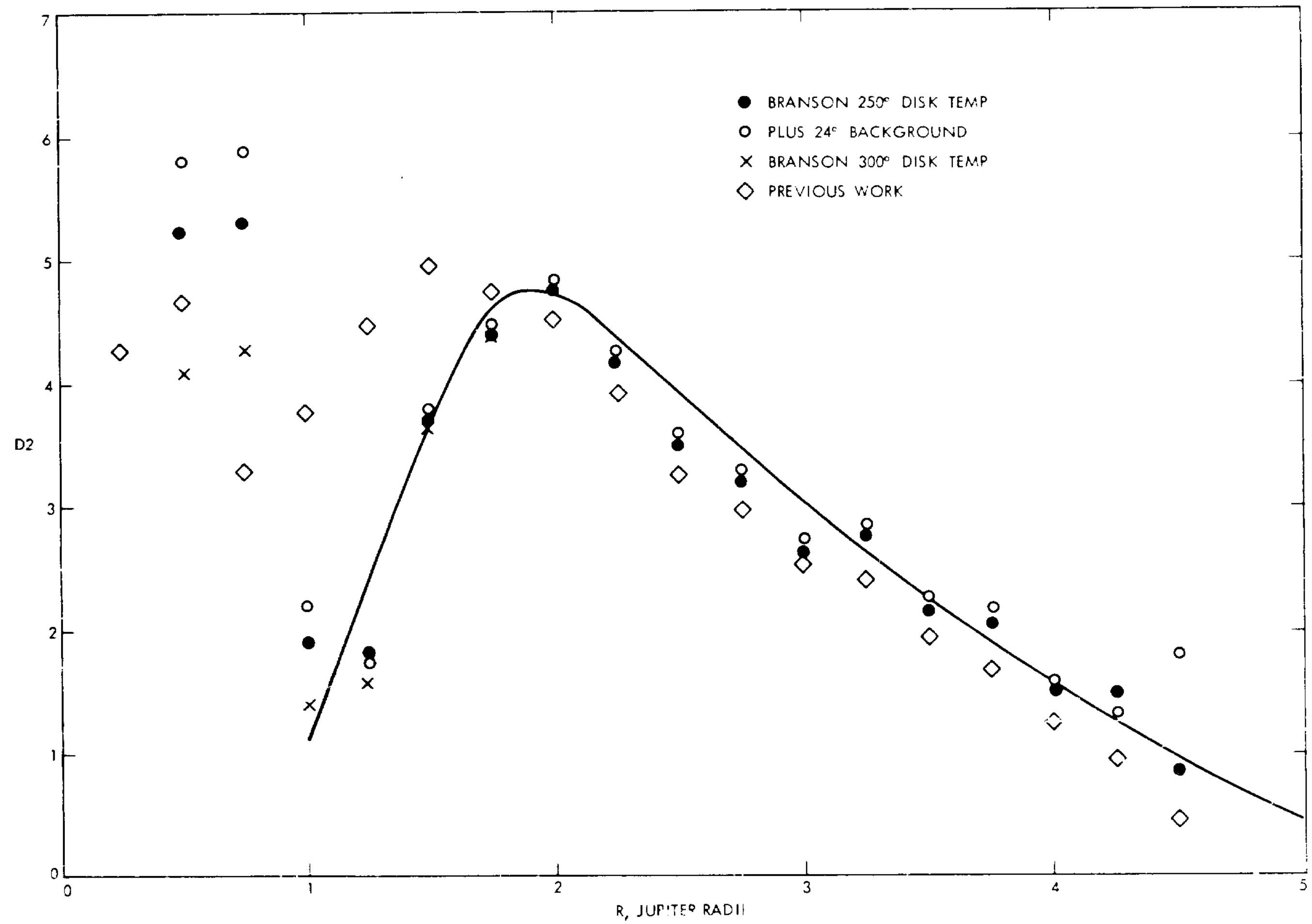

Figure 1. Source Intensity Per Unit Volume, Derived from Branson's Data at 21 cm Wavelength

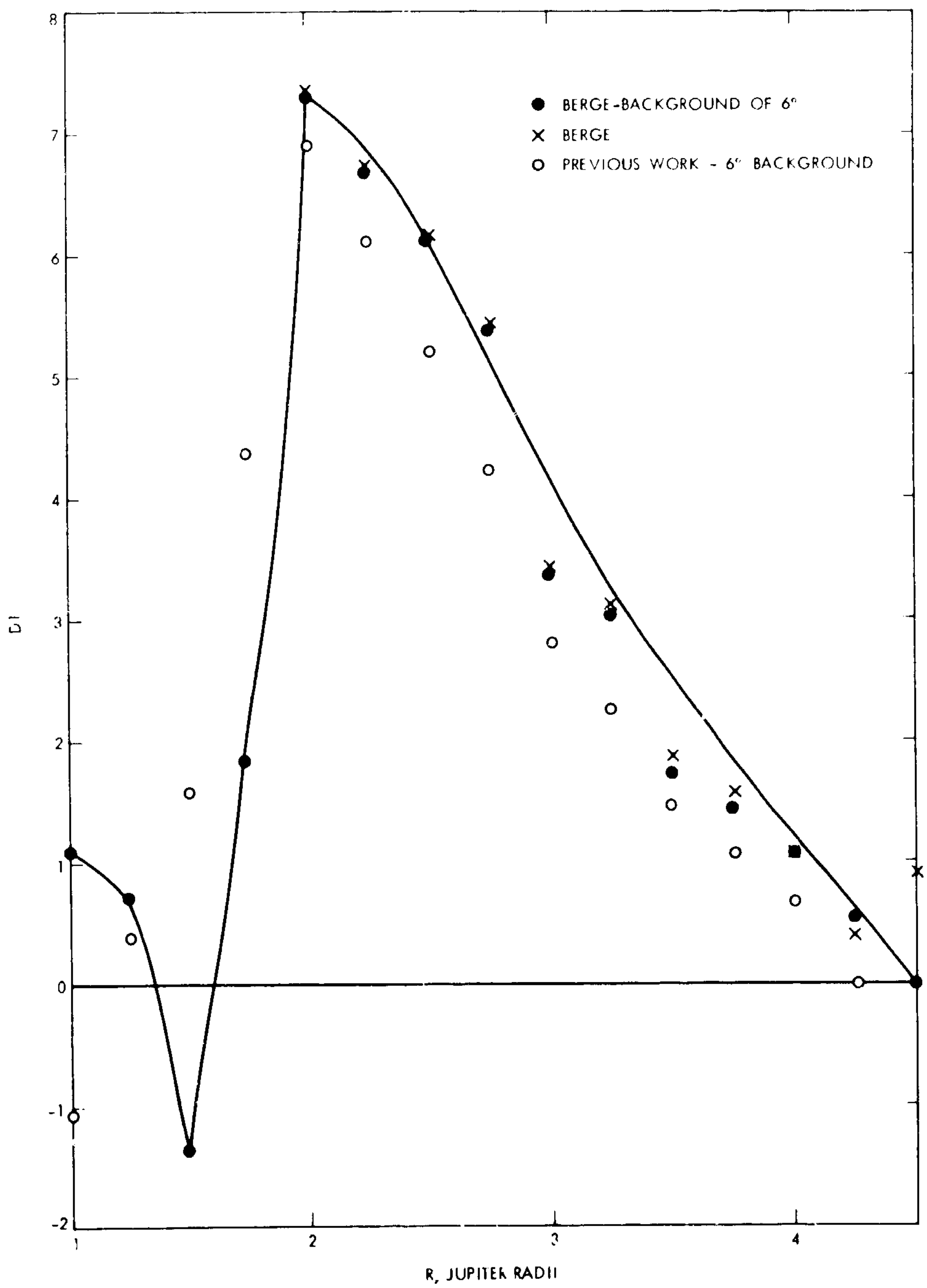

Figure 2. Source Intensity Per Unit Volume, Derived from Berge's Data at 10.4 cm Wavelength

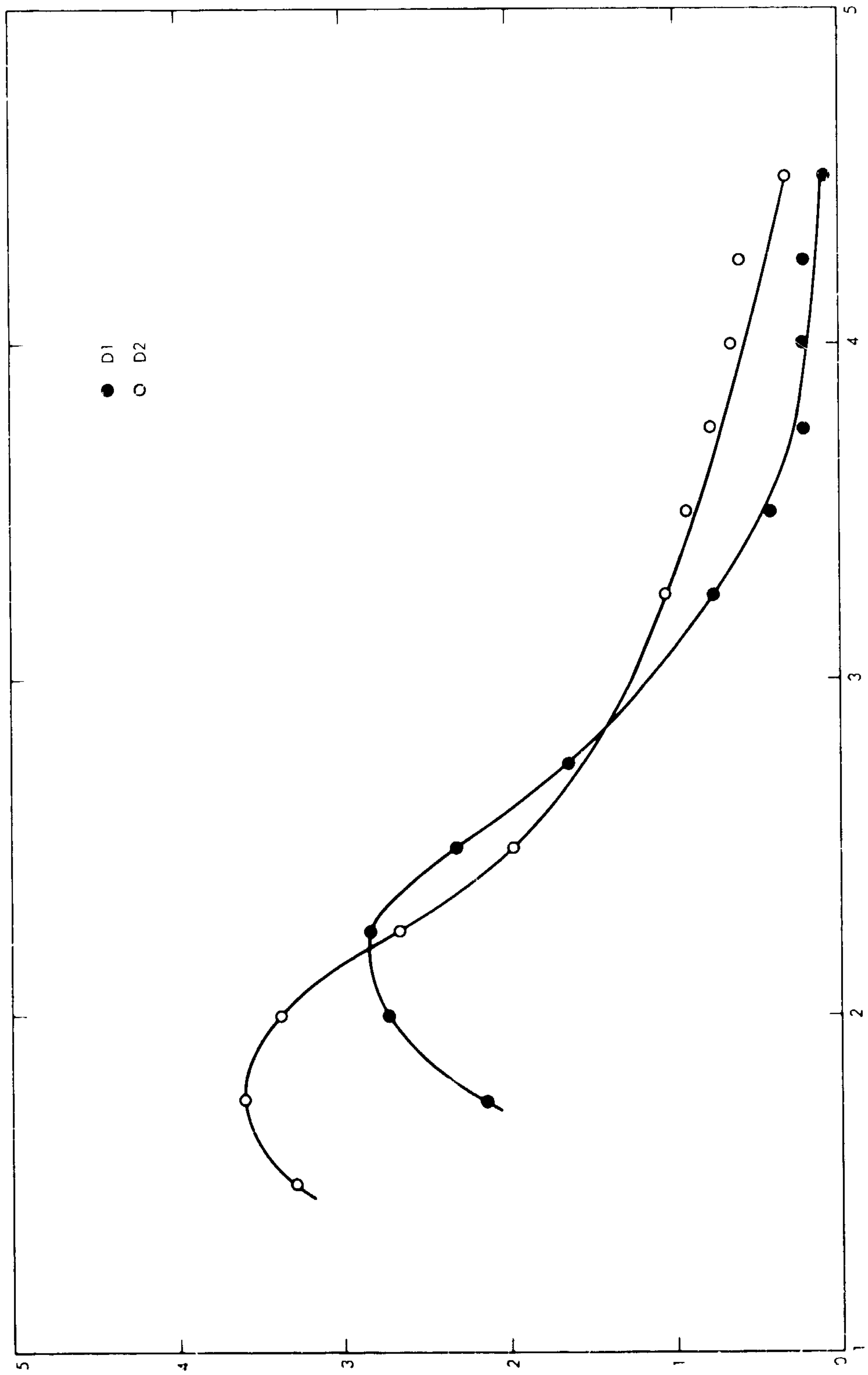

Figure 3. Revised Source Intensities Per Unit Volume Derived from Data at 10.4 and 21 cm Wavelengths

Taking the ratio of the source intensity per unit volume at the two frequencies Berge and Branson observed and comparing this ratio with the theoretical result Dr. Luthey reported on earlier, we find the electron temperature as a function of distance in Figure 4. The maximum occurs at about 2.5 R_J and is about 100 Mev. For $R > 2.5\ R_J$, the result is $E_0 \sim r^{-3}$; for $r < 2.5\ R_J$, the result is $E_0 \sim r^6$. The inner behavior of the temperature leads to a constant electron lifetime for energy loss of about a year, requiring the injection time of the electrons to be a year.

It is important in any comparison of Branson's and Berge's observations to make sure that the comparison is made for the same Jupiter longitude. Dr. Berge has very kindly made available a new improved analysis of his data. Unfortunately we missed that he had changed to a different Jupiter longitude and it will take us another week or so (*at that time*) to correct our analysis for this. From our past experience, we expect this change to make some difference but it will not change things very much.

We would like to emphasize that the primary difficulty we have in obtaining the correct relative intensity of the two observations. The analysis is unavoidably sensitive to the ratio of their intensities. If we lower Berge's intensity by 10% relative to Branson's observation, we find that the electron temperature is lowered by a factor of three. The electron density is inversely proportional to the square of the electron temperature.

To summarize briefly, we find that the electron temperature increases for $r > 2.5\ R_J$ with decreasing r as $1/r^3$ reaching a peak of about 100 Mev at $r = 2.5\ R_J$. For $r < 2.5\ R_J$, the electron temperature goes as r^6 because of the energy lost to radiation. The lifetime (hence also the injection time) is about one year. We are finding the analysis for $r < 1.75\ R_J$ very difficult to continue because of what we think is a high density of low-energy electrons (with low pitch angles mirroring close to the poles), an eccentricity of the magnetic dipole, and some uncertain data. We are continuing to polish our analysis but the final results will not differ qualitatively from what are reported here.

What we have given so far is the facts about the electron energy and density. What I have now to say about protons should better be

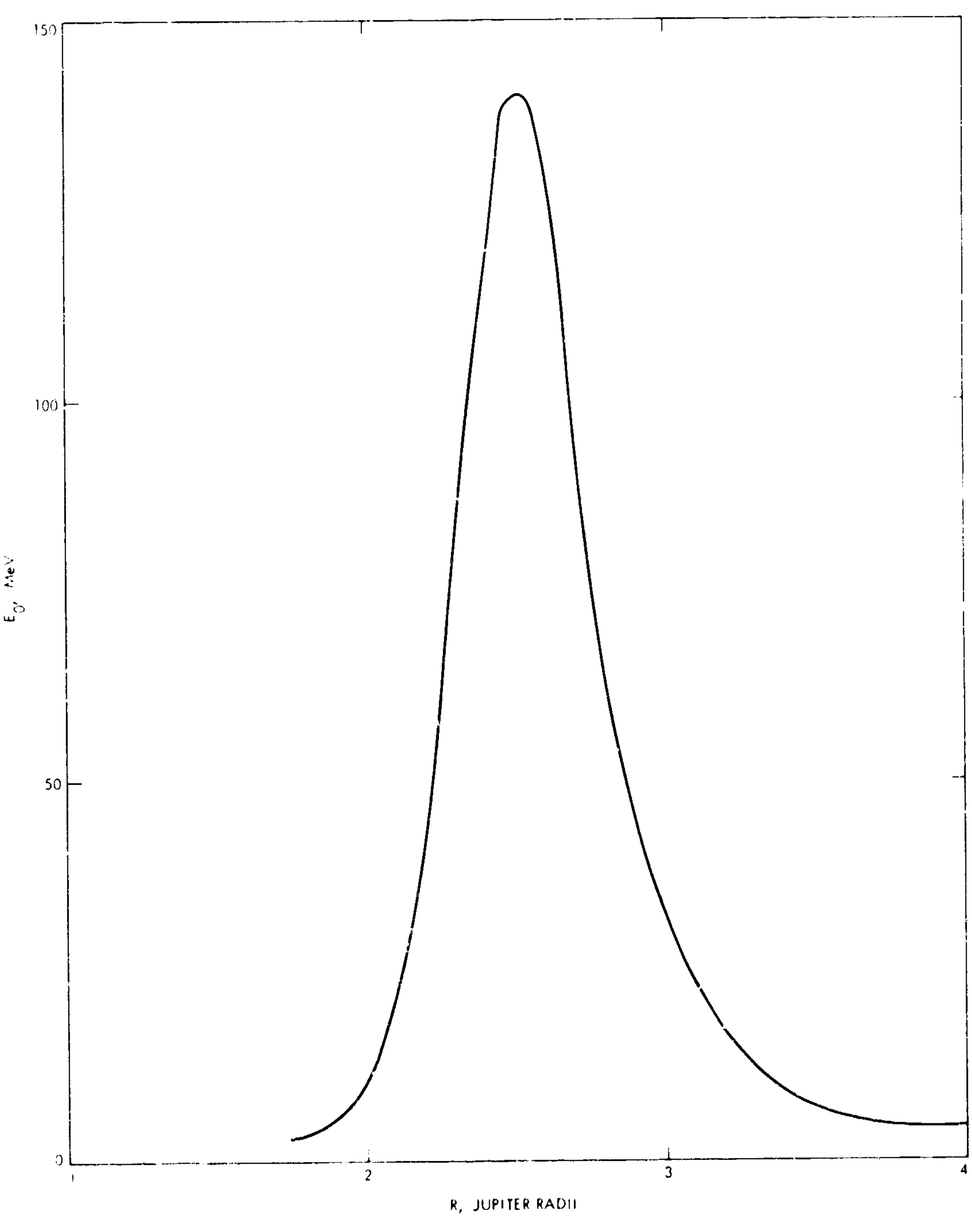

Figure 4. Electron Temperature, Based in Part on the Ratio of Source Intensities at 10.4 and 21 cm Wavelengths (Figure 3)

entitled *fantasy*. We have concluded that electrons diffuse in from the magnetosheath increasing their energy as $1/r^3$ and then for $r < 2.5\ R_J$ lose their energy due to radiation loss. Protons diffuse in to the Earth's field in a day or less, but Jupiter's field is much stiffer. A 500 eV proton in the magnetosheath diffusing in with an increase in energy as $1/r^3$ would have an energy of 100 MeV near the surface of the planet. They do not lose energy by radiationloss. They might amount to a serious environmental hazard for a Jupiter orbiter or flyby mission. To bring attention to the problem and illustrate the necessity of further study, I would like to describe here the consequences of making an *upper estimate* on the proton flux by assuming the magnetic field is loaded with all the energetic protons it can hold.

We expect the protons to have an energy of 100 MeV/L^3 where L is the equatorial distance from the planet center in units of planetary radii. Hence, they will have a velocity of $1.4 \bullet 10^{10}\ L^{-3/2}$ cm/sec. We believe electrons diffuse in in one year and that atmospheric losses are slower. This is reasonable because we estimate Jupiter's atmospheric scale height to be about 1/100 of that on Earth expressed in planetary radii. For an upper estimate, we assume that the proton energy density is equal to the magnetic field energy density in a dipole field with an equatorial surface field of 7 gauss. This gives us the remaining upper limit to the quantities of interest.

Energy density, $B^2/8\pi = 2L^{-6}$ ergs/cc
Proton number density, $10^4\ L^{-3}$/cc
Proton-flux, $1/4 \bullet 10^{14}\ L^{-4.5}$ particles/cm^2/sec
Energy flux, $2 \bullet 10^3\ L^{-7.5}$ watts/cm^2

These are frightening upper limits (as shown below):

R	1	2	2.5	3	6
Energy (MeV)	100	12	6.4	3.1	0.46
Density (cm^{-3})	10^4	$1.2 \bullet 10^3$	640	370	40
Proton flux	$1.4 \bullet 10^{14}$	$6 \bullet 10^{12}$	$2.3 \bullet 10^{12}$	10^{12}	$4.5 \bullet 10^{10}$
Energy flux (watts)	2000	11	2.1	0.52	$2.9 \bullet 10^{-3}$

Our proton energy and velocity estimates seem to us fairly reliable; our upper limit to the number density is probably much higher than what will actually be observed. At least, we hope that it is. Professor Warwick yesterday discussed his inferences from observations of the Faraday effect in which he concluded that at two Jupiter radii, the number density of all electrons times the optical depth is about 3×10^{12}. If we assume that the optical depth is a radian times the distance to the planet, we have an optical depth of 14×10^{9} cm. Hence, the total electron number density is 200/cc, that is, one-sixth of the value proposed as our upper limit for protons.

DISCUSSION

MR. THOMAS: Would 8 W/cm^2 of protons be detectable in some kind of an auroral display if they were near the surface?

DR. BEARD: Phil Morrison told me that the innermost satellite of Jupiter, which is nothing but a rock 70 km in dimensions, looks very much brighter on one side than it does on the other side. He was suggesting that there might be some fluorescence of energetic particles to bring this about.

DR. HESS: How could you make that asymmetric?

DR. BEARD: Because of the drift of the protons.

DR. HESS: Usually they would all drift into it from one side.

DR. BEARD: More from one side than from the other.

DR. LUTHEY: I know of only one investigation where someone tried to look for the hydrogen Lyman alpha line at Jupiter by means of a photographic plate. As I recall, he had seven plates, and two of them showed a possible hydrogen Lyman alpha line. That's not quite conclusive.

MR. KLOPP: That was very chancy, as I recall, Joe.

DR. WARWICK: There have been about five or six investigations like that. The most recent have been in the last month, and there has been no positive H-alpha aurora discovered on Jupiter, but the upper limits to it are at less than one kilorayleigh, which I think is much less than these limits of energy. I would like to make one comment. With that kind of energy flux into the atmosphere of Jupiter, you would think it would be decisively overriding in the infrared flux measurements that are currently being interpreted as indicating a very marginal enchancement of infrared emission compared to the insulation at a certain level. This is in terms of erg/cm^2 — (10^5 or maybe less) and in terms of infrared emission, perhaps twice the insulation.

Now it sounds to me like these energies are orders of magnitude larger than the observed infrared emission. Is that correct?

DR. BEARD: Yes. But there is an important thing about this. When you talk about infrared emissions or auroras as a rate, if these particles get gobbled up, then the particles aren't there anymore. The diffusion time this close to Jupiter is at best an order of several years. If there was any process that gobbled up the particles, then the particles wouldn't exist near Jupiter's atmosphere. It would cut it off. What we're talking about is an ambient proton population in which nothing is there to gobble them up, and what you are talking about is a rate of particles.

DR. WARWICK: I agree. But you are talking about fluxes of energy stably trapped, to be sure, which are thousands or more factors larger than the planetary emission. Although I haven't made a computation, I suspect that you are quite close to an upper limit calculation which would violate the infrared emission.

DR. DAVIS: I think you can avoid this argument about the rate when the stuff gets into the planet by considering this little rock[1] (*satellite of Jupiter*) which is fairly close, because this is going to be getting the full 10 10 W/cm^2 of flux. It is going to be a nice glowing red.

DR. BEARD: That's right[2].

DR. WARWICK: No; but it isn't.

DR. BEARD: But there <u>is</u> an important *BUT*, and that is that the rock may very well clean out this area. The atmosphere may very well clean out this zone. We are talking about things outside of this, because it would be a rate. If you can observe it, then it would gobble it up, and there wouldn't be any particles at that point.

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[1] *the innermost satellite of Jupiter, Amalthea*

[2] *author's note added later: "2 watts/cm^2, at most"*

DR. DAVIS: This J5 won't do that. Since J5 has a very small radius, it won't clean out this zone very fast. Besides, it is at 2.5 R_J, so maybe you could get this inside. Anyway, there are a couple of other points that I would like to worry about on your electron analysis, and let me try to bring these up very briefly. In order to carry out this analysis, you break space up into zones 0.25 R_J in width and solve a set of simultaneous equations to get the density in each of the zones. The observations have a certain amount of uncertainty in them. If you solve many simultaneous equations, the results, in general, become much more uncertain than the uncertainties in the original items on the right-hand side. Have you made any estimate as to how uncertain your quantities for which you solve are in terms of the uncertainties in the data?

DR. BEARD: Yes. This analysis is very unstable to changes in the initial data. I didn't show it. If you change the original data, then what happens is that you are having to change source intensities, and if you make this source intensity large, you have to make this source intensity very small, and they add up, and the whole thing goes to pot, and it just becomes a big zigzag[3]. There are things that I left out that might have been worthwhile mentioning. On the plots, particularly out here at large Jupiter radii where you are not certain what the background is, you get a point here. This point will be higher up. We can raise this point. We can raise the background and this point will drop; this other point will rise and both will be on the same line. Well, you saw the Berge model in which I think the intensity near the planet was underestimated, producing an enormous sag...In fact, he got negative source intensities. If you had, for instance, the correct ideal flux, then the thing would be a lot smoother, but the moment that you begin to wave the line around, then you don't get any reasonable plot for the source intensity. It is <u>very</u> unstable data.

DR. DAVIS: You speak of the energy of the electrons E_0. I take it this is the characteristic energy for the Maxwell-Boltzmann distribution.

DR. BEARD: That's correct.

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[3] *author's added note: "In our present analysis, things seem much more stable."*

DR. DAVIS: Suppose that it isn't a Maxwell-Boltzmann distribution. Suppose that it is more like an exponential distribution. How much is that going to modify your analysis?

DR. BEARD: Not very much. You get something that is really quite comparable if you choose an $E^{-\gamma}$ distribution. Dr. Luthey has been doing that at the University of Iowa.

DR. LUTHEY: If you choose an $E^{-\gamma}$, you can get different gammas across and then the problem is to find out what the average energy or characteristic energy is. Then you compute the energy intervals, and that, in general, tends to increase as you get further out. It goes as $1/\sqrt{\pi}$.

DR. BEARD: But the important thing is that the energy responsible for the radiation is about the same as you get from the Maxwell-Boltzmann distribution.

DR. LUTHEY: Right. The biggest difference occurs where E_0 gets very, very large, because there you have to move the energy distribution out to the higher energy, and it falls off so fast. It would fall faster than if you just used a power logarithm, which would give you a lower characteristic energy. What I am saying is that at low energies, the two are roughly comparable. At higher energies, the Maxwellian suffers a little bit.

DR. LIEMOHN: Is it fair to say that you have a very narrow energy band here that allows you to use most any distribution you choose because all you are doing is saying the number of particles over a given energy band is the same?

DR. BEARD: That is probably true. What you are saying is then it doesn't matter what the energy distribution is that we use. We come out with about the same energy of particles either way of doing it that are contributing to the radiation, and that follows from what you said.

DR. THORNE: Can I come back to the proton problem?

DR. BEARD: Incidentally, people refer to these estimates of proton intensities. I am not trying to give estimates! I am trying to give an upper limit which should be brought down.

DR. THORNE: If you had particles hitting the little piece of rock[1] at 2.5 R_J, what is the critical flux before you actually see the emissions?

DR. BEARD: These protons are rather ineffective in producing much emission. But the point I really want to emphasize is that anything which will absorb particles just means that they aren't there and you wouldn't observe the flux.

DR. THORNE: Well, you would observe it, because there is some diffusion flux into the orbit, but that is very, very timely. The diffusion flux into the orbit of the innermost satellite is going to be very small, so that actually seeing emissions from that satellite--if you do have interreactions between particles and the sunlight--probably wouldn't be seen.

DR. BRICE: Dr. Beard, may I ask how firm is that 10^{-6}? Does this come from your latest calculation where you have folded the pitch angles? That would make a factor of about one-hundred different, I think. You said that the ratio of the electron energy density to the magnetic field energy density is 10^{-6}, and I recall that is the number you game me sometime; and I think your model has changed to *up* that.

DR. BEARD: What was our electron density before?

DR. LUTHEY: 10^{-4} on the planet surface down to 10^{-6}.

DR. BEARD: Now that is 10^{-3}. So it is about ten times more.

DR. LUTHEY: Previously, the number density was fairly independent of the magnetic field. Now it is dependent on the magnetic field with an isotropic distribution of pitch angles.

DR. BRICE: I think this is a very important number--the best, if you like, in contribution from the electrons. I think this is really the best clue as to what the protons are likely to be.

DR. BEARD: This is energetic electrons though.

DR. BRICE: That's correct. My concern is that we get as strong a number as we can for the energy density of the energetic electrons. I think for the upper limits that you have discussed, assuming a diffusion time of a year, you will need such incredible energy sources that it is very difficult to visualize.

DR. BEARD: I estimated what this was--how much of the solar wind got in--and it was down by __ (I have forgotten how many orders of magnitude)--but it was down by a tremendous number.

DR. BRICE: In energy or density?

DR. BEARD: No, I just considered the energy of the solar wind on the magnetosphere and the amount of energy that is radiated by the electrons is really negligible compared to that energy.

DR. BRICE: That is true. Six orders of magnitude.

DR. SMITH: I wanted to talk about the protons in this very scary proton model.

DR. BEARD: Upper limit?

DR. SMITH: I was interested in some of the implications associated in taking the solar wind protons and walking them down into this field through several gauss. It seemed to me that one of the implications would be, of course, that the pitch angles become very, very flat. You have a kilovolt or less parallel to the field, and you are getting up to ten to a hundred MeV across, so you are going to end up with very, very flat pitch angles.

DR. THORNE: Parallel increases like L^2.

DR. SMITH: What I was wondering is how narrowly confined such a distribution of particles would end up being. How close to the equator would they be?

DR. KENNEL: No scattering would be about 25 to 1.

DR. BRICE: The ratio would be just about the ratio of the L values to where you are to the L value to where you injected them. If they are injected at L=50, you would then look at them at L=2; then, you would have a 15 to 1 ratio, roughly.

DR. SMITH: If you go down to L=2, where are the particles mirroring?

DR. BRICE: Very close to the equator.

DR. KENNEL: On the other hand, I don't think you can assume that they are going to retain this flat pitch-angle distribution in the distant Jovain magnetosphere, because at L=10, they can probably diffuse in as an isotropic flux at L=10, and then you would work from there. The most you would get would be about three.

DR. SMITH: But to really change those pitch angles, you are talking about putting a lot of energy in parallel--essentially putting several MeV in.

DR. KENNEL: You take MeV out of the perpendicular and scatter them parallel.

DR. SMITH: With waves?

DR. BRICE: If you just conserve the first two invariants and violate the third, that is going to happen. You are going to get tens of MeV into the perpendicular and MeV into the parallel just conserving the first two invariants and violating the third.

DR. SMITH: Are there other reasonable scattering models, then, which would enable you to get particles into, say, L=2 at 10 MeV or one-hundred MeV energy that are mirroring-off the equator?

DR. DAVIS: I looked up a number which I think was in mind. I think the general order of magnitude of the solar energy flux of Jupiter is someting like $10^4/cm^2$, which is a very small fraction of this 10 W/cm^2. Too, you have to say that you certainly don't get 10 W/cm^2 of ion particles hitting this J5, or it will, as I say, be glowing much hotter than sunlight. You say, "Okay. We get rid of this because it sweeps them out, and it reduces the energy flux in the cosmic traps. Strike it back by the order of 10^3 or something like that." But that means if it can do that, these other larger satellites further out (of at least a thousand times the cross sectional area) probably will sweep out these high energy particles much more effectively so that they will never get in.

DR. BEARD: That is the point that Dr. Hess wants to raise.

DR. WARWICK: Before you get into that matter, you have got to ask whether the thing was right in the first place...that the basis on which he is estimating the high proton fluxes is correct, nearly.

DR. BEARD: I am not estimating high proton fluxes.

DR. WARWICK: I just don't think it is right from the beginning.

DR. BEARD: What you are saying is that you have a better upper limit.

DR. WARWICK: No. I am saying that the data analysis which gives that very extremely sharp peak on the unfolding of Branson's data, just doesn't look to me reasonable. I did want to ask a specific question which was what is the half-width of the peak data in terms of seconds of arc projected on the sky? That is the data that is essentially the source for these wild fluctuations in energies and fluxes and so on.

DR. BEARD: You misspoke. The sharp peak came from the Berge model. The data on Branson's peak was much, much more broad.

DR. WARWICK: It was not Berge's model, per se. It was your analysis of Berge's model.

DR. BEARD: You were referring to Branson's peak, and it wasn't Branson's peak.

DR. BRICE: Dr. Warwick, we are up against precisely the same problem that someone brought on earlier. You are trying to solve what is, in essence, an integral equation. To solve that, you have to differentiate it, and when you're differentiating and trying to solve for almost as many parameters as you have data points, you are going to get wildly uncertain answers. Nonetheless, they appear to be the best ones that we have.

DR. WARWICK: I disagree.

DR. BEARD: Why do you disagree?

DR. WARWICK: The point is that the technique of unfolding the data which you have used, which is, in principle, correct, is in practice shown to be wildly unstable. Therefore, you don't push against a technique which is a correct one in principle; you don't continue to push that. You look for methods that are stable, and there are methods that are stable which don't require the fine subdivision of the data that you have used.

DR. BRICE: I think what you are saying is that you might just as well take the data and take the back of an envelope and come up with the calculations for the energies and the number densities, and you will be close to right.

DR. WARWICK: You will be a lot closer to right.

DR. BEARD: Let me say this, that out beyond 2 R_J, I think the results are quite reliable. The difficulty is that big hole near the planet produces an instability in the calculations for neighboring rings, so that the top of the peak and the points nearer the planet are completely untrustworthy, but I believe beyond that, the analysis is okay.

DR. WARWICK: Are we talking now about a hundred MeV electron energies? I am not sure.

DR. BEARD: We are talking about the distribution of electron energies beyond the peak at 2 R_J. Now, the peak at 2 R_J gave one-hundred MeV. I mistrust that. I think it is more like 50 MeV. But beyond that, I think the analysis is correct.

DR. WARWICK: I mistrust it, too. I think it is more like 5 MeV, and the analysis that I propose is certainly a lot more stable than yours. You are raising the question here: are these particles, and have we got to get rid of them because they will make the satellites glow?

DR. BEARD: We are talking about protons. To produce the glow requires that one assumes an upper estimate of the proton flux that we have given.

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THE EFFECT OF JUPITER'S SATELLITES ON THE DIFFUSION OF PROTONS

Gilbert D. Mead*

The material that Dr. Hess and I will be talking about is quite overlapping. In fact, the idea of the effect of Jupiter's satellites on its radiation belts is one which he has had for some time, and it is just in the last month or two that we have been trying to put more specific numbers into the concept. We worked to some degree together and to some degree independently; therefore some of the things I have worked out are somewhat overlapping of his. Since we haven't had much time to interact, there may be relatively minor inconsistencies between some of the numbers I have worked out and some of the numbers he has worked out, but we are discussing the same concept.

Our main point is that there is one major difference, besides all of the scaling factors, in going from the Earth to Jupiter. That is the presence of Jupiter's satellites, and, in particular, their effect on radial diffusion, a process which we feel is one of the most important source mechanisms on Earth, particularly for protons.

What we have tried to do, then, is to put some numbers into the problem, and these numbers involve such concepts as bounce periods and drift periods. We have to be very careful when we talk about which drift periods we mean, so I would like to spend some time discussing Tables I and II. If you take, first of all, Table I, we assume that Jupiter's surface field is 10 gauss. I should really stress that whenever I talk about the surface field, I mean the equatorial field, which means 20 gauss at the poles, if we have a centered dipole.

The numbers in Table I are derived from equations that are found in any radiation belt textbook. The cyclotron radius scales as the magnetic field, but since the magnetic field on Jupiter is about 40 times as

**Laboratory for Space Physics, NASA Goddard Space Flight Center, Greenbelt, Maryland 20771*

Table I. Parameters of Equatorially-mirroring Protons at $3R_J$*

*for a Jupiter surface equatorial field of 10 gauss

Cyclotron Radius R_C			Bounce Period τ_B		Drift Period τ_D	
Kinetic Energy of Protons	Earth	Jupiter	Earth	Jupiter	Earth	Jupiter
100 keV	40 km	1.1 km	13 sec	140 sec	2.5 hrs	1 yr
1 MeV	125 km	3.4 km	4.1 sec	45 sec	15 min	40 days
10 MeV	400 km	11 km	1.3 sec	14 sec	1.5 min	4 days
100 MeV	1300 km	35 km	0.4 sec	5 sec	0.15 min	10 hrs

Table II. Characteristics of Trapped Protons Near Jupiter's Satellites

Parameter	JV (Amalthea)	JI (Io)	JII (Europa)	JIII (Ganymede)	JIV (Callisto)
Satellite Diameter (km)	150-200	3500	3100	5550	5000
Semimajor Axis (R_J)	2.5	5.9	9.4	15.0	26.4
Eccentricity and Inclination	~0	~0	~0	~0	~0
Sidereal Period	12 hrs	1.77 days	3.55 days	7.2 days	16.7 days
Synodic Period[1]	60 hrs	13.1 hrs	11.2 hrs	10.5 hrs	10.2 hrs
B, at Satellite[2] (γ)	63,000	5000	1200	300	55
Cyclotron Radius[3] ($R_C \propto E^{1/2}$)	2.3 km	29 km	120 km	4800 km	26,000 km
Bounce Period[3] ($\tau_B \propto E^{-1/2}$)	38 sec	1.5 min	2.4 min	3.8 min	6.5 min
Drift Period[3] ($\tau_D \propto E^{-1}$)	48 days	20 days	13 days	7 days	5 days

[1] in frame of rotating planet

[2] for a Jupiter equatorial surface field of 10 gauss

[3] for a proton with energy E~1 MeV and pitch angle α~90°

large as on Earth, the radii are down by a factor of 40 or so from comparable values on Earth.

The bounce periods scale essentially as the size of the planet, and since Jupiter's radius is ten times as large, the bounce times will be approximately ten times as long for the same energy particle at the same L value.

The drift period scales as $B_0 R^2$. This factor gives very, very much longer drift periods on Jupiter than on Earth, and this is one of the big things that must be kept in mind in comparing the physics of the particles on the two planets. We see that drift periods of a few minutes on Earth become many days on Jupiter. We shall see later, however, that the corrotation drift period will be a more important factor.

Table II shows the characteristics of trapped protons near Jupiter's satellites. I have worked out some numbers characteristic of each of these satellite positions to see how they effect the physics of the problem.

First are shown some characteristics of the satellites themselves. The synodic period is an important one, because we are assuming in all of our studies that the entire magnetosphere and all the particles within the magnetosphere will corrotate along with the 10-hour rotation period of Jupiter, at least as far as Jupiter IV--the satellite Callisto. Therefore, what is of interest is the relative motion of the moon compared to the corrotation motion. The satellite JV is almost synchronous with Jupiter's rotation period and thus has about a 60-hour synodic period. Others will appear, if you are in a corrotating frame, to move backwards with periods as shown, around 10 to 13 hours.

The magnetic field at each of the satellites is shown, assuming 10 gauss at the surface. We then show various numbers calculated for a 1-MeV proton. The cyclotron radius is relatively small for the nearby satellites, but it can get quite large for a 1-MeV proton near the outer satellites.

The bounce periods are of the order of minutes for 1-MeV protons, and the drift period, due to the gradient drift, is of the order of a few days (a period long compared with the apparent motion of the moon). So, if you want to compare drifts with respect to one of the satellites, the synodic corrotation period of the satellite is the important period to use. This is much shorter than the gradient drift period.

Now it turns out to be more interesting to think in terms of a particle at each of the different satellites which conserves its adiabatic invariants. Therefore, Table III shows some comparable numbers for a proton that conserves its first adiabatic invariant. We picked protons with energy of 100 MeV at L=1.3, where B=4.5 gauss. That corresponds to protons with a magnetic moment of 20 MeV per gauss.

If the magnetic moment is conserved, the proton kinetic energy at each of these satellites will range from 14 MeV to 12 kilovolts. This leads to different values for the other quantities of interest. The cyclotron radius, R_c, ranges from about 8.6 kilometers to a maximum of 280 km at Callisto, always much less than the satellite diameter. Thus, although it appeared from Table II that at the outer satellites, the radius of curvature became quite large compared to the satelite itself, under conservation of the first invariant, the rate of curvature is always small compared with the satellite.

The bounce period, τ_B, now varies much more rapidly with distance, ranging from 10 seconds to 60 minutes.

The drift period at Jupiter is given by

$$\tau_D = \frac{180,000}{L\ E}$$

with E in MeV and τ_D in minutes. This is for 90-degree pitch-angle nonrelativistic particles. The drift times calculated from this range from 3.5 days to about 400 days.

Table III. Proton characteristics near Jupiter's satellites assuming conservation of the first adiabatic invariant (magnetic moment). Values are given for a proton with E/B = 20 MeV/gauss, assuming an equatorial of surface field of 10 gauss

Parameter	JV (Amalthea)	JI (Io)	JII (Europa)	JIII (Ganymede)	JIV (Callisto)
Proton energy at Satellite	14 MeV	1.1 MeV	260 keV	65 keV	12 keV
Cyclotron Radius R_c	8.6 km	30 km	60 km	120 km	280 km
Bounce Period τ_B	10 sec	1.4 min	4.7 min	15 min	60 min
Drift Period τ_D	3.5 days	18 days	50 days	110 days	400 days
Mean Life Near Satellite Before Impact	20 days	2 days	12 days	20 days	100 days
Typical Diffusion Time	-------	100 years	1.5	30 days	0.1 day

Now, what does this say about the physics of trapped protons near Jupiter's satellites?

First of all, these drift periods are, in general, very long compared with the motion of the satellites in the rotating frame of reference. The synodic period of the satellites is of the order of 10 to 15 hours. The drift periods are much longer. Therefore, the synodic periods listed in Table II are the appropriate ones to use to describe the drift periods of the protons with respect to the satellites, when we calculate the shadowing effect.

The next thing to do is to estimate whether, in one-half bounce period, the proton drift relative to the satellite will move it in longitude a distance large compared with a satellite diameter or small compared with a satellite diameter. This is important in order to determine whether the absorption of protons by the satellites is a stochastic process or not, and also, whether it is possible for a particle as it bounces at the same radius as the satellite to miss the satellite by drifting past between bounces.

It is straightforward to calculate this, and it turns out that for particles of these energies, over this whole region, the longitudinal distance between successive bounces is of the order of a few satellite radii. Therefore, the particles could easily come by and miss the satellite.

You might think, initially, that if the proton is bouncing very, very rapidly, as on Earth, when it comes to the satellite, the satellite just has to wipe it out. Well, that is not necessarily true, because it can make one bounce in front of the satellite, and the next bounce it might move past the satellite. So it is kind of a stochastic process.

DISCUSSION

DR. KENNEL: At each satellite, there is a certain critical particle energy at which the bounce comes back exactly 1 satellite radius away. Have you computed that energy?

DR. MEAD: It could easily be computed from this analysis, but I can't give you that immediately. That is true. There is a certain energy at each satellite where the amount of drift per bounce is exactly 1 satellite diameter.

DR. WARWICK: It is almost exactly 1.1 MeV. It is relative to the plasma at 54 kilometers per second. If you multiply that times 84 seconds, you get the diameter of Io

DR. MEAD: When you go to the outer satellites, it tends to be a few satellite diameters.

DR. KENNEL: So Io is the dangerous one.

DR. MEAD: No, they are all dangerous. This is basically going to be a pretty stochastic process. You might hit it, but more likely, you will miss it each time you go past, but if you go past enough times and if it stays in the vicinity of the satellite long enough, there will be a wipeout with a stochastic low rate. So, this is the basic assumption we are making.

Now, the next thing one can do is make two kinds of calculations using very simplified assumptions.

In the first case, we assume that you have perfect symmetry, that the dipole is located exactly in the center of Jupiter, and that the satellite distance is precisely the same all the time (which, by the way, is true for the innermost satellites, since their eccentricity and radiation are extremely small). Suppose now there were particles bouncing at exactly the same radius as the satellite. How long would it take for a fraction 1/e of the these particles to be lost due to the stochastic probability process of striking the satellite?

From the geometry of the problem, we can calculate that the 1/e mean lifetime is given by

$$\tau_{mean} = \frac{\pi \tau_B L R_J}{D_s}$$

where $L R_J$ is the distance out to the satellite and D_s is the satellite diameter. It does not depend upon the drift period. It depends upon the bounce period, because the more bounces it makes, the greater probability it has of hitting the satellite.

DR. BEARD: That doesn't mean you approximated the satellite diameter as a square?

DR. MEAD: Yes, that is true. In this case, it is taken as a square. I worked out another case, where we assume that for various reasons, one being the offset of the dipole, another being any other of the asymmetries that might make this distance somewhat fluctuating, we can define a region ΔR, within which that satellite is likely to be located. Now, within that region, the satellite now appears in cross section as a circle. Now, suppose that the particle is going to bounce somewhere in the region ΔR. If again we assume stochasticty, we can take the whole area of this region and compare it with the area of the satellite and make the same kind of calculation.

DR. BEARD: Does that mean you are taking into account an off-center of the dipole?

DR. MEAD: Yes, that is right. This ΔR could mean the off-center of the dipole. In this case, the mean life is given by

$$\tau_{mean} = \frac{4\tau_B L R_J \Delta R}{D_s^2}$$

It now depends upon the square of the diameter, which is more realistic.

DR. BEARD: It will also be a larger number.

DR. MEAD: No, not necessarily; because the ΔR is going to be of the order of D_s, so that the two numbers will be about the same. It turns out that if you use $\Delta R \approx 4$ or 5 satellite diameters, then this will increase the lifetime by some small amount. Now if we assume that ΔR is about 15,000 km, i.e., a few satellite diameters; we get the mean lifetime indicated in Table III, ranging from 2 days at Io to about 100 days at Callisto. The mean lifetime at JV (*Amalthea*) is longer than at Io because of its much smaller diameter. Now, to see whether this is going to effectively get rid of the protons as they diffuse in, we have to compare these lifetimes with some characteristic time that the proton will be in the in the region ΔR and, therefore, subject to being wiped out, as you might say, by the satellite. So, to do this, you have to put in some concept of diffusion and estimate how rapidly a particle is going to move past each satellite by diffusion. Now, here is where you get very large uncertainties, depending upon whether you use the kind of numbers that Dr. White used earlier or whether you take numbers similar to those that Nakada and I used in our proton diffusion problem and then try to make some reasonable extrapolation to Jupiter. If you take magnetic storms, which are the source of diffusion in the Nakada-Mead model, and assume that in each 24-hour period that you could get a magnetic storm that is likely to move the magnetopause at Jupiter, inward, so as to double the surface field at the planet, you get a diffusion constant at Jupiter that leads to the diffusion times shown on the last line of Table III. This diffusion time is the typical time that a proton would stay in the vicinity of these satellites.

DR. HESS: What do you mean in the vicinity? You mean to move the satellite diameter?

DR. MEAD: I actually took a ΔR of about 10,000 km. The diffusion time ranges from 100 years at Io to about 0.1 days at Callisto. Now this diffusion time is an extremely sensitive function of L, as you can see. It has very, very long times at Io and relatively short times at Callisto.

DR. BRICE: With the same diffusion, how long would it take to get your electrons in?

DR. MEAD: The electrons would take the same time as the protons.

DR. BRICE: So it would take 100 years for this diffusion to move an electron in the distance of Io?

DR. MEAD: Yes.

DR. BRICE: We are hung up on this 1-year lifetime.

DR. MEAD: We do not claim that the same diffusion rates apply to electrons.

DR. HESS: We have based it on terrestrial experience. You are getting into _my_ talk here.

DR. MEAD: This would say that protons pass Callisto in a relatively short time compared to the wipeout time; that Ganymede might begin to do a pretty good job of wiping out protons, and it certainly looks like protons require quite a long time to diffuse past Europa, and they just couldn't survive this long. Certainly, if they got past Europa and got near Io, Io would wipe up whatever is left. Now, let's be careful of what our assumptions are. First of all, one assumption is that the satellite itself does not alter the magnetic field topology in which the proton moves. In other words, because the satellite is there, the protons aren't going to move around the satellite as the satellite pulls the field lines along with it in some sense. This is a basic assumption, and to the degree that there is any influence of the satellite on the magnetic field environment and electric field environment which causes corotation, one would have to modify this theory. Dr. Hess has a few ideas as to what kind of influences satellites might have.

We also assume that if in a bounce period, a proton hits a satellite, then that proton is gone. It is not useful for anything else. One might argue that protons will perhaps scatter off the surface and do something else. We have not looked into this. There is one other thing that one might ask here: to see whether there is any way you can get around this absorption by satellite. The dipole is tilted in 10 degrees and one must consider what effect this will have. If the satellite is as much as 10 degrees above the magnetic equatorial plane, a particle (*proton*) with a relatively large equatorial pitch angle (particles whose mirror-lattitude is less than 10 degrees) might mirror before it gets to that latitude and somehow never hit the satellite and be able to wiggle its way through!

One must look at the drift period and realize that even though there might be a time at which the axis was tilted at 10 degrees and a proton happened to be below the axis, as the particle drifts in longitude, it will eventually get up to the geographic equator about a quarter of a revolution later. Then when the satellite comes around, it will wipe it out, even if it has a 90-degree pitch angle. The particle lifetime might be lengthened by about a quarter of the drift time, so that at Europa, for example, instead of a mean lifetime of 12 days, it might have a 20-day *mean* life. For a while, it might get by, but eventually it will get absorbed by the satellite.

DR. WARWICK: The same argument holds for the off-center dipole. That is to say, displaced from the axis of rotation, those particles which are in the correct longitude relation, every 13 hours are brought back inside of Io, but their longitudinal drift after your....

DR. HESS: If you displace the dipole vertically, then you have got some that can sneak by.

DR. WARWICK: That is another story. That's right, though. They would sneak by, but I was talking about (with respect to the axis of rotation) the same argument which would hold true for the tilted dipole, so that the time would be a little bit longer; but not a whole lot longer.

DR. MEAD: These are basically the numbers I have worked out; Dr. Hess has worked out the shadowing effect for protons. He will also discuss why we haven't looked at the electrons.

ENERGETIC PROTONS IN JUPITER'S RADIATION BELTS**

Neil Brice*

Estimation of the location, density, and energy of energetic protons in the Jovian radiation belt is a difficult task since there are no measurements known to relate directly to these particles. As a result, the estimates will be somewhat uncertain and must be based on models of the Jovian outer environment. The best approach to building a model of the Jovian magnetosphere appears to be scaling from the Earth's magnetosphere, bearing in mind that there are serious potential pitfalls in this approach, since some factors which may be safely ignored in first order theory for Earth will be important for Jupiter and vice versa. These are most likely to arise when some dimensionless parameter is much larger than unity for earth but much smaller than unity for Jupiter, or vice versa.

Magnetic Field Model

The basic physical constants of Earth and Jupiter are given in Table I. The values of these constants plus the magnetic moment, solar wind parameters, and properties of the Jovian ionosphere will be needed to construct the model. Average solar wind parameters measured at Earth and expected values at Jupiter are given in Table II.

Table I. Physical Constants of Earth and Jupiter[1]

	EARTH	JUPITER
Radius	6400 km	70,000 km
Distance to Sun	1 a.u.	5.2 a.u.
Rotation period	24 hr	10 hr
Surface acceleration of gravity	9.8 m/sec^2	24.5 m/sec^2
Surface field	0.3 gauss	1 gauss 10 gauss

[1](after Brice and Ioannidis, 1970)

* *School of Electrical Engineering, Cornell University, Ithaca, N. Y. 14850*

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Table II. Average Solar Wind Parameters at Earth and Expected Values at Jupiter[a]

	EARTH	JUPITER
Density	7 protons/cm^3	0.26 protons/cm^3
B_{sw}	7 γ	1 γ
$B_\perp$	1.5 γ	0.3 γ
Angle to radial	45°	80°
Pressure	4×10^{-17} Nt/m^2	7×10^{-19} Nt/m^2
Velocity	400 km/sec	400 km/sec
Travel Time	104 hr	540 hr

[a]Values are given for the density, flow velocity (and resulting pressure), travel time from the Sun, the magnitude of the total solar wind magnetic field strength (B_{sw}) and a typical magnitude for the component normal to the ecliptic plane ($B_\perp$). (after Brice and Ioannidis, 1970)

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For Earth, the distance to the bow of the magnetopause is found by balancing the pressure of the terrestrial magnetic field with that of the solar wind. If the extent of the Jovian magnetic field in the solar direction is determined by a balance between magnetic field pressure and solar wind pressure (see, for example, Beard, (1960)), the distance to the bow, R_{bow}, will be given by

$$R_{bow} = R_J \left(\frac{2B_{SJ}^2}{\mu_o N m \, V^2} \right)^{1/6}$$

where R_J is the radius of Jupiter, B_{SJ} is the surface field at the equator, μ_o is the magnetic permeability of free space, N is the solar wind number density, m the particle (proton) mass, and V the solar wind velocity. Using the parameters of Table II, we obtain 26R_J for a surface field of 1 gauss and 53 R_J for a 10-gauss surface field (compared with 10 R_E for Earth). The boundary of the terrestrial magnetosphere is generally well defined and the shape well known (at lease in the equatorial plane). The distance to the boundary in the dawn-dusk meridian is about 1½ times the distance to the bow, and beyond this point the tail flares out at an angle of about 10 degrees. A sketch of the field-line shape is given in Figure 1. Note that in the extended "tail," field lines are essentially "open" while in the "body" of the magnetosphere, field lines

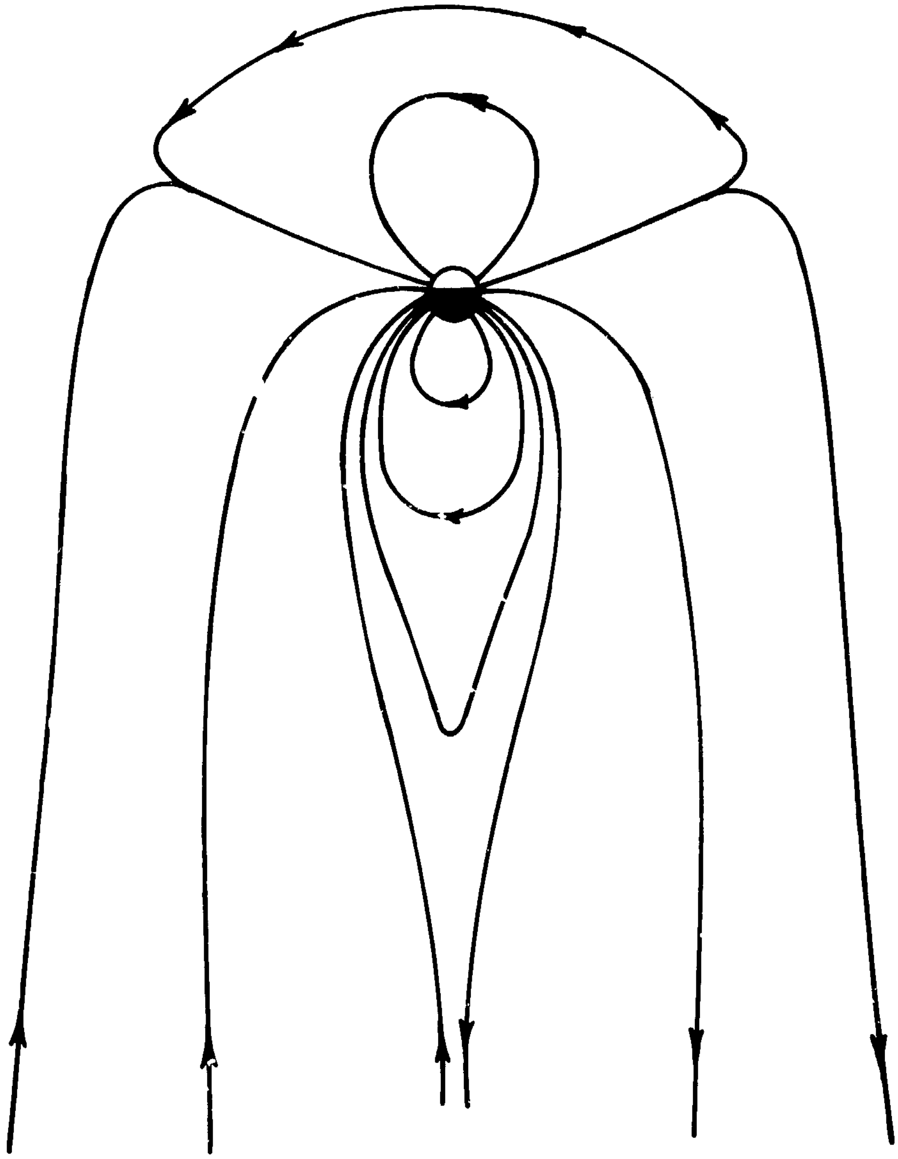

Figure 1. The magnetic field shape for Earth and the expected shape for Jupiter. In this figure, the bow side magnetopause is at 10 planetary radii, which is appropriate for Earth. For Jupiter, the size of the planet should be reduced to make the distance to the bow 30-50 R_J.

are closed. Thus the magnetosphere is naturally divided into two regions, one of open field lines and one of closed field lines.

In models of the Earth's magnetosphere (Williams and Mead, 1965) the shape of the magnetic field structure is independent of solar wind pressure. The only "free" parameter is the distance to the bow measured in the planetary radii. Thus, to get a scaled model of the magnetic field configuration of Jupiter, the same magnetic field shape as for the Earth is used and the size of the planet is then scaled to give the correct distance to the bow in planetary radii. In Figure 1, the distance to the bow is 10 Earth radii, but to scale this figure for Jupiter with a 10-gauss field, we need only reduce the size of the planet 5.6 times to make the distance to the bow $56R_J$, and we then have the expected magnetic field configuration for Jupiter. Near the surface of the planet, the solar wind influence on the magnetic field shape is negligible (i.e., the field may be approximated by a dipole) so that the open field line-closed field line boundary can be mapped from the terrestrial to the Jovian polar cap using a dipole magnetic field. The open field line region then has a radius of 9 degrees or 6 degrees for surface fields of 1 and 10 gauss with dayside colatitudes of 6 degrees and 4 degrees, respectively.

At this point, we should note that for Earth, the corotation velocity at the magnetopause boundary is much less than the solar wind velocity, whereas for Jupiter, the corotation velocity at the boundary is larger than the solar wind flow velocity. Thus, while the velocity differential across the boundary is about the same on the dawn and dusk sides of the terrestrial magnetosphere, it is quite different for Jupiter (the velocity change is much larger across the dawn boundary) and this may lead to dawn-dusk asymmetries for Jupiter which are not observed on Earth.

Large Scale Electric Fields (Magnetospheric Convection)

The frictional drag across the magnetopause boundary produces large scale motion within the magnetosphere and associated time-varying electric fields. These electric fields are typically 1-2 kV per Earth radius (R_E) (Brice, 1967) and if they are scaled to Jupiter, we obtain about 1-2 kV per

Jupiter radius (Brice and Ioannidis, 1971). The ratio of this electric field to the corotational electric field is unity for Earth at about 5 R_E, whereas for Jupiter, the corotational field should dominate everywhere inside the magnetopause (see Figure 2). Thus, unless the frictional drag at the magnetopause is much larger for Jupiter than for Earth, the convective electric fields will be relatively smaller for Jupiter than for Earth. These fields may be responsible for inward diffusion and acceleration of energetic particles.

There is an additional boundary within the magnetosphere which appears to have little significance for Earth but may be very important for Jupiter. This separates the region dominated by gravitation and one dominated by centrifugal force. The distribution of thermal plasma will be greatly affected by the magnitude and direction of the net (centrifugal plus gravitational) force. In the equatorial plane these balance at 2.2R_J for a corotating magnetosphere. For the plasma distribution, since plasma diffuses preferentially along the magnetic field, the important factor is the net component of force in the magnetic field direction. The dashed line in Figure 3 is the locus of points in a meridional plane where these components are balanced. (Since the forces are not in general colinear, this locus meets the equator not at 2.2 R_J, but at slightly less than 2 R_J.) For the Earth, the forces balance at about 6.5 R_E, which is beyond the "plasmapause." Here the plasma is not in diffusive equilibrium, and the velocity is not dominated by corotation so that no substantial difference is noticed between the plasma distribution inside and outside this boundary. The same should not be true of Jupiter, where the boundary is much closer to the planet and substantial effects should be noticed.

Cold Plasma Density Distribution

The cold plasma density distribution is significant to the problem considered here for two reasons. Firstly, for a corotating magnetosphere, since the centrifugal force dominates gravity near the equatorial plane beyond about 2 R_E, the magnetosphere acts as a potential well and can trap plasma entering this region from the ionosphere below. This plasma should be confined to photo-electrons from the ionosphere and associated "cold" protons (Ioannidis and Brice, 1971). This plasma can escape by interchange instabilities

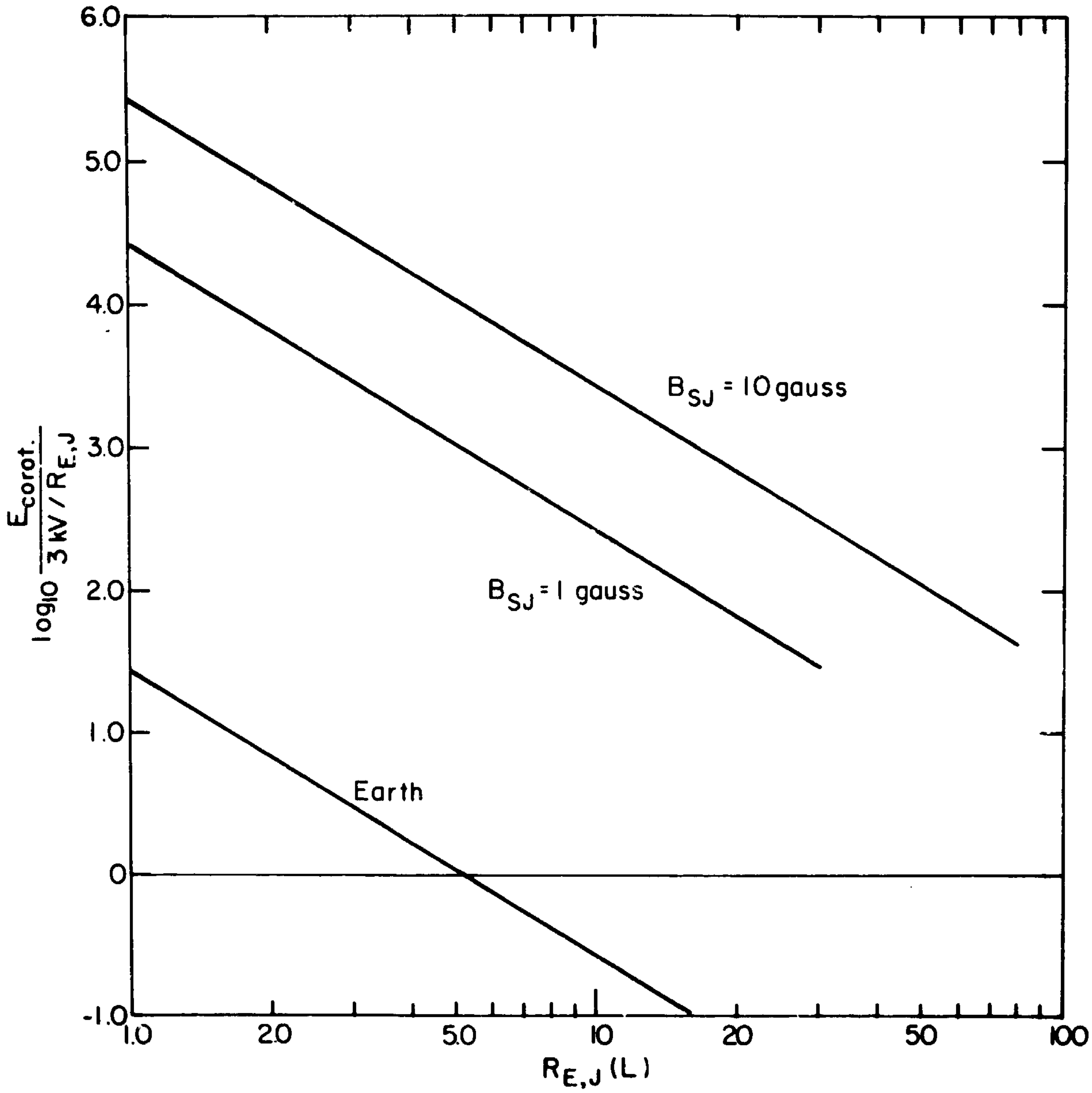

Figure 2. The logarithm (to base 10) of the ratio of convective electric field to corotation electric field for Earth, and for Jupiter, assuming surface fields of 1 and 10 gauss.

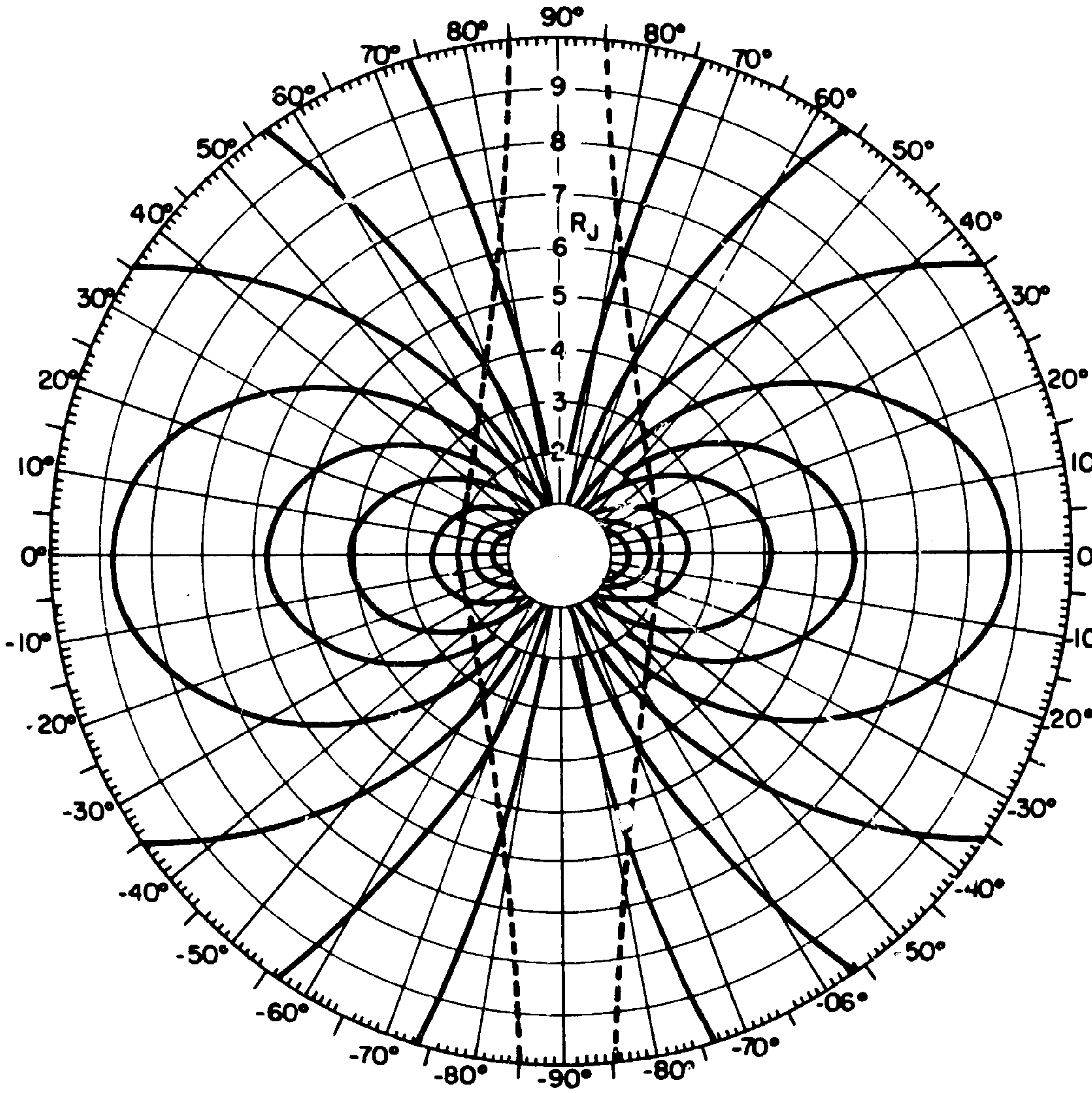

Figure 3. The location in the equatorial plane as a function of latitude and radial distance of the boundary between regions in which the force along magnetic field lines is dominated by gravity and the region dominated by centrifugal force for a corotating magnetosphere.

through the magnetopause, but before it reaches this distance, it is expected that the energy density of the corotating plasma will exceed the magnetic field energy density. This is likely to produce ballooning instabilities along the magnetopause and a turbulent, rough boundary. The relatively large plasma pressure inside the magnetopause may move out the distance to the bow, and by producing a rough boundary, may increase the frictional drag between the solar wind and the magnetosphere. A model equatorial plasma density distribution derived by Ioannidis and Brice (1971) is shown in Figure 4. In addition to effects associated with trapping and loss of cold plasma in the magnetosphere, the density of cold plasma is likely to control the "characteristic energy" of the medium, *viz*, the magnetic energy density per particle, $B^2/2\mu_0 N$--where N is the particle number density. Energetic particles with energy greater than a few times this characteristic energy are subject to limits on the number of particles which may be stably trapped by the magnetic field. These limits arise from instabilities which produce ion cyclotron waves (through resonance with energetic protons) or whistler-mode waves by interaction with energetic electrons.

Energy Sources

The principal source of free energy in the terrestrial magnetophere is the solar wind. The typical energy incident on the terrestrial magnetosphere is about 10^{12-13} watts, of which about 1% or 10^{10-11} watts is injected into the magnetosphere (Axford, 1964). For Jupiter, the incident energy is about 10^{15} watts. Using the Axford drag model, the energy injected into the magnetosphere is calculated to be 0.9 and 4×10^{13} watts for 1 and 10 gauss surface fields respectively, while for Dungey-Petschek drag we get 1 and 3×10^{13} watts, respectively. These again are very close to 1% of the incident solar wind energy flux. Estimates of parameters relating to convection of the magnetosphere are summarized in Table III.

Photoelectrons from the terrestrial ionosphere have fluxes of a few 10^8 for Earth with a mean energy of about 20 eV, giving a total input of almost 10^9 watts. If the photoelectron flux scales with the incident solar illumination, we estimate about 2×10^9 watts input into the Jovian magnetosphere.

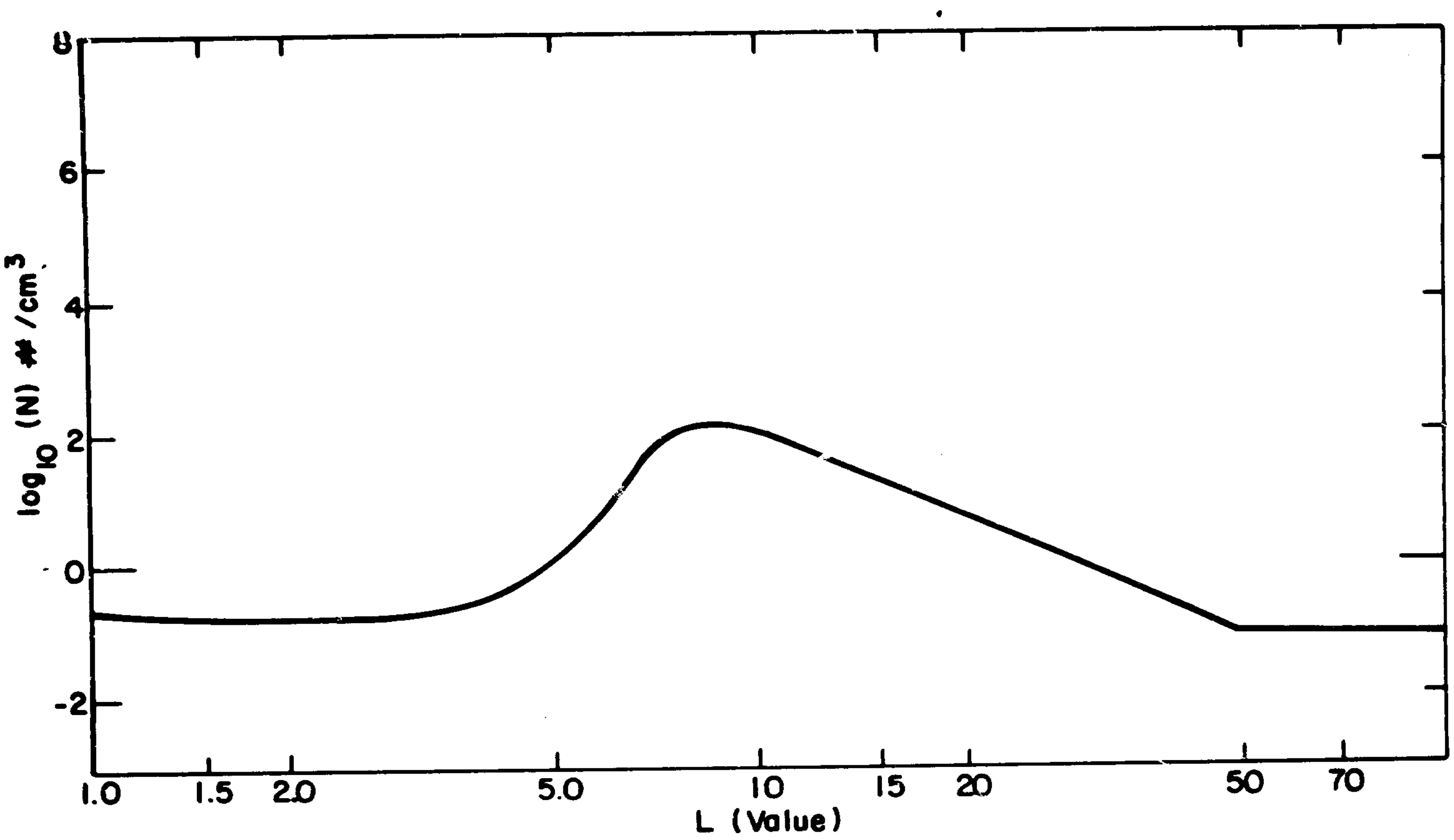

Figure 4. The expected distribution of "cold" plasma in the equatorial plane of Jupiter as derived by Ioannidis and Brice (1971). The "temperature" is about 10 volts and the plasma is confined to within about one planetary radius from the equatorial plane.

Table III. Parameters Relating to Magnetospheric Convection[a]

Surface Field Model	1 gauss		10 gauss	
	Axford	Petschek	Axford	Petschek
E field electrostatic (kV/R_J)	2	3	1.25	3
Potential (kV)	131	230	180	480
Energy input (watts)	9×10^{12}	10^{13}	4×10^{13}	3×10^{13}
Corotational electric field	$\frac{9.1 \times 10^4}{L^2}$	kV/R_J	$\frac{9.1 \times 10^5}{L^2}$	kV/R_J
Integrated Pedersen conductivity	20-200 mhos		2-20 mhos	
Joule heat	5.10^{11}-5.10^{12} watts		10^{11}-10^{12} watts	

[a]Parameters relating to magnetospheric convection. For assumed surface fields of 1 and 10 gauss and the Axford and Petschek models of solar wind drag, estimates are given of dawn–dusk electrostatic electric fields in the equatorial plane and the corresponding potential across the magnetosphere, together with estimates of the energy input. Using assumed values of the height integrated Pederson conductivities, the associated Joule heating of the ionosphere is estimated. Note that if the polarity of Jupiter's magnetic field is opposite to Earth, the convective electric field will be directed from dusk to dawn, not dawn to dusk.
(after Brice and Ioannidis, 1970)

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Beyond about 6 R_J, protons diffuse outwards. The flux will be about the same as the flux of photoelectrons into the magnetosphere. The corotational velocity of the protons at the magnetopause gives them an energy of about 1 kV, and this represents an energy source of about 10^{11} watts. Piddington and Drake (1968), Brice (1968), and Goodreich and Lynden-Bell (1969) have suggested that the interaction of satellites with the Jovian magnetic field may produce energy through currents along field lines between the satellite and the conducting ionosphere. The energy input is estimated to be about 10^{11} watts if the only significant source of resistance is the ionosphere, where the height-integrated Pedersen conductivity is estimated to be about 20 mhos [using the Gross and Rassool (1964) model ionosphere]. This energy would come from the rotational energy of the planet as the effect of Io is to partially stop a small part of the ionosphere from corotating. If the whole ionosphere were prevented from rotating by the magnetosphere (a highly unlikely event), the energy input to the magnetosphere would be about 10^{18} watts. For Earth, most of the solar wind energy input is deposited in the polar cap in an area about twice that of the open field line region. The energy input to this part of the polar cap ionosphere is a few ergs/cm^2 sec, or about the same as the EUV solar luminosity deposited in the mid-latitude ionosphere. For Jupiter, the solar wind energy deposited on the polar cap could be as large as 100 ergs/cm^2 sec. Thus, the solar wind energy tends to be the dominant energy source for the terrestrial polar ionosphere (large zenith angles reduce the solar EUV input) and should completely dominate the Jovian polar ionosphere. The total solar input (about 10^6 ergs/cm^2 sec or 1 kW/m^2 at Earth) of course dominates all the above energy sources, but only a tiny fraction of this is deposited in the outermost atmosphere.

An additional small energy input comes from the 10-degree tilt between the magnetic axis and the rotational axis. The energy input is given by

$$W = \frac{2 M^2 \Omega^4}{3 \mu C^3} \sin^2(10°)$$

where M is the magnetic moment, Ω the angular rotation, C the velocity of light in vacuum, and μ the permeability of free space. This gives about 10^5 watts for Jupiter, and a fraction of a milliwatt for Earth. This is believed to be the principal source of energy loss for the "pulsars" (Pacini, 1967) but is not significant for Jupiter.

Energetic Particles

Potential sources of energetic particles in the Jovian magnetosphere are the solar wind and cosmic rays, as well as the interaction between Jupiter's inner satellites and the magnetic field as suggested by Piddington and Drake (1968), Brice (1968), and Goldreich and Lynden-Bell (1969).

Beyond the bow shock boundary where thermalization occurs, solar wind protons will have energies of the order of 1 keV at Earth and Jupiter. The magnetic moment, μ, of these particles in the solar wind is then about 15

MeV/gauss at Earth or 100 MeV/gauss at Jupiter. Electrons in the solar wind behind the terrestrial bow shock have energies about one-fifth to one-tenty that of the protons. Thus, the magnetic moment expected to electrons is about 20 MeV per gauss at Jupiter. Unless the fields experienced by the particle change substantially during a gyroperiod, the first adiabatic invariant will not be violated and μ will be constant. Violation may occur in a "neutral sheet" where the magnetic field goes to zero and the gyroperiod becomes very large, or in the presence of large amounts of electromagnetic noise near the gyrofrequency (whistler mode noise for electrons, Alfven waves for protons). If we assume that μ is conserved, as a solar wind proton which diffuses in to 7 planetary radii (L=7) would have an energy of about 13 keV for Earth, or 2.6 MeV for Jupiter. For L=2, we get 500 keV for Earth; 100 MeV for Jupiter.

Trapped energetic particles have two components of drift, one due to corotational and convective electric fields and the other due to gradients in the magnetic field. The former causes drift along electrostatic equipotentials (i.e., perpendicular to E) at constant energy. The latter may cause drift across equipotentials (i.e., parallel or anti-parallel to E) with associated change in energy. If the convective electric field is fluctuating in magnitude (as it does on Earth) this can cause energization and diffusion of energetic particles associated with violation of the third adiabatic invariant (for a discussion of adiabatic invariants, see Northrup, 1963).

The period for magnetic field gradient drift around the Earth for terrestrial trapped particles is given by[1]

$$T = \frac{3(1 + \epsilon)m_e R_E G}{\epsilon(w + \epsilon)m R_0 F} \quad \text{hours}$$

where $\epsilon = \gamma - 1$ is the kinetic energy/mc^2; R_0, the equatorial distance to the magnetic shell on which the particle drifts; m_e, the electron mass; m, the particle rest mass; and G/F is a factor which varies from 1.0 to 1.5 for

[1] *Lew, 1961*

particles with pitch angles in the equatorial plane of 90° and 0°, respectively (i.e., mirror points in the equatorial plane or at very low altitudes). The drive period scales as the magnetic moment of the planet and inversely as the distance from the center of the planet, so that for the same L value (i.e., distance measured in planetary radii) the drift period is about 3 orders of magnitude longer for Jupiter than for Earth. The period for Jupiter is given by

$$T = \frac{1100(1 + \varepsilon)m_e R_J G}{(2 + \varepsilon)m R_0 F} \quad \text{hours}$$

For Earth, this drift is typically much faster than corotation. (For a 40-keV electron at L=7, the drift period is a few hours.) At Jupiter, the rotation is faster, while the drift is much, much slower, so that this "grad B" drift is much slower than corotation, and the total drift velocity will be very close to the corotation velocity. One can readily calculate the minimum time required to bring a solar wind particle to the given L value (i.e., to a given energy, assuming μ is concerved), by third invariant violation driven by convective electric fields. It is assumed that the convective electric field is uniform and is switched from zero to its maximum value in perfect synchronism with the particle drift (i.e., with a cycle time very close to 10 hours). For Jupiter, the number of particle orbits for L=7 is about 100, giving a minimum acceleration time from 1 keV to 2.6 MeV of 10^3 hours. If the acceleration is not synchronous but quasi-random, then 10^4 orbits will be required or 10^5 hours. As the particles approach the planet (*Jupiter*), the energy gain required to conserve μ increases rapidly (as B, i.e., as L^{-3}) while the potential across the orbit decreases (as L) so that to accelerate a particle to L=2 by convection electric fields, would take at least 10^5 hours and diffusion would take 10^9 hours. For Earth, the computed diffusion times of about 1 hour for L=7 (13 keV) and 100 hours at L=2 (500 keV) are consistent with observations of injection of energetic particles associated with large magnetic storms. These parameters are summarized in Table IV.

The only "direct" information on energetic particles near Jupiter comes from the decimetric emission from Jupiter, which is generally interpreted as synchrotron radiation coming from relativistic electrons

Table IV. Parameters of Injected Solar Wind Particles[a]

	Earth	Jupiter
μ_{sw}	15 MeV per gauss	100 MeV per gauss
T_{Drift}	3 hr	~10^3 hr
Rotation period	24 hr	10 hr
L = 7 { K.E. →	13 keV	2 6 MeV
L = 7 { $T_{Diffusion}$ →	1 hr	10^5 hr
L = 2 { K.E. →	0.5 MeV	100 MeV
L = 2 { $T_{Diffusion}$ →	10^2 hr	10^9 hr

[a]Parameters relevant to energetic particles injected from the solar wind, including the first adiabatic invariant (the magnetic moment) in the solar wind, μ_{sw}, a typical drift period for energetic particles, the energy reached and time required for diffusion by third invariant violation to distances of 7 and 2 planetary radii, respectively, driven by time-varying convective electric fields.

(after Brice and Ioannidis, 1970)

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trapped in the Jovian magnetosphere (see for example Carr and Gulkis, 1969 or Warwick, 1967). In order to deduce the energies in the protons, the most fruitful approach appears to be to look for sources for the electrons, and then evaluate these for protons. As noted above, possible sources of energetic particles are cosmic rays, satellite-magnetosphere interaction and the solar wind. Cosmic rays do not appear to be able to provide an adequate energy source deep in the magnetosphere (at 1.5-2.0 R_J) and the electron energies likely to be produced by interaction of satellites with the magnetic field is only a few keV, which is too low to be a source of the relativistic synchrotron-emitting electrons. The energies of these electrons are consistent with diffusion in from the solar wind with conservation of the first adiabatic invariant. The next major question is "What is the driving source for this diffusion?" At sufficiently large distances, magnetic field disturbances associated with changes in solar wind pressure, electric fields associated with convection or interchange instabilities driven by plasma density gradients all can provide adequate diffusion. However, at distances less than 10 R_J, these become increasingly

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unsatisfactory. The most plausible source of large-scale magnetospheric electric fields close to the planet appears to be neutral atmospheric winds and turbulence. If the wind velocities producing these electric fields in the ionosphere are roughly independent of latitude, then the electric fields in the equatorial plane will increase with decreasing distance, varying roughly as L^{-3})where L is the equatorial distance measured in R_J). A velocity normal to the magnetic field of 100 meter/second gives an electric field of 0.1 V/meter in the ionosphere (for a 10 gauss field) or $(7/L^3)$MV/R_J in the equatorial plane. This will be larger than the expected convective electric fields within about 10 R_J. While the suggestion that upper atmospheric winds may be the dominant source driving the inward diffusion of energetic particles within 6 - 10 R_J needs further evaluation, it is clear that, because of the much larger surface magnetic field on Jupiter, this effect must be much stronger for Jupiter than for Earth, and it appears at this time to give a plausible explanation of how solar wind electrons might be diffused in to 1.5 R_J.

One must then ask "If the electrons are diffused in, what factors are likely to differentiate between electron and proton diffusion?" As has been pointed out by Hess and Mead at this conference, the satellites of Jupiter may sweep out the radiation belt particles in their path and the inward diffusion must be rapid enough to avoid this if the particles are to penetrate the satellite orbits. Because the protons have somewhat more energy than the electrons, their diffusion will be somewhat slower and it is conceivable, but perhaps not likely, that the diffusion is just fast enough to permit the electrons in, but just slow enough to sweep out the protons. A second factor arises because the protons have a much larger Larmour radius. If the satellites have sufficiently high conductivity then the magnetic field will not penetrate them but will sweep around them. For very highly conducting satellites, with no magnetic field penetration, the area in which particles were swept out would be the product of the satellite circumference and the particle Larmour radius, since only particles with guiding centers on magnetic field lines within one Larmour radius of the satellite would be lost. This area would be much larger for protons than for electrons, but much *much* smaller than the satellite cross-section, and probably so small as to not be a major factor in sweeping out the radiation belt.

While the two factors described above might lead to larger densities of energetic electrons than protons, the synchrotron radiation near the planet from the relativistic electrons will be much larger than that from the protons of comparable energy, so that while electron fluxes may be reduced within 2 - 3 R_J by this effect, proton fluxes would not be so influenced. The principal loss mechanism for the protons is expected to be collision with the particles of the neutral atmosphere near the surface of the planet.

For the inward-diffusing particles, the fluxes may be sharply reduced to the Kennel and Petschek (1966) stable trapping limit if the particle energies are much above the magnetic field energy per particle. The threshold energy varies with equatorial distance, and if one uses the plasma density curve in Figure 4, it is apparent that a large distances where $N \alpha L^{-4}$ and $B^2 \alpha L^{-6}$ that $B^2/N \alpha L^{-2}$, where L is equatorial distance measured in units of a planetory radius. For conservation of the first adiabatic invariant, the particle energy will vary as L^{-3}, so that the ratio of particle energy to threshold energy for the instability increases as the particles diffuse in, and if one uses the first invariant of 100 MeV per gauss for protons, and the plasma densities shown, the proton energy will exceed the threshold energy for the instability around 8 R_J where the maximum plasma density occurs. If the energies are above the threshold, then the maximum number which can be stably trapped is independent of the cold plasma density, as the number density per unit interval in particle parallel velocity which can be stably trapped $[F_{max}(V_R)]$ decreases as the parallel velocity squared, and may be expressed as

$$F_{max}(V_R) = \frac{N \log \left(\frac{1}{R}\right) c^2 \Omega_i}{\pi^2 \, \pi_i^2 \, L \, A}$$

which may be reduced to

$$F_{max}(V_R) = \frac{B \log \left(\frac{1}{R}\right)}{\pi^2 \, L \, A \, \mu_o \, V_R^2}$$

where N is the plasma density, c is the velocity of light, Ω_i and π_i are the ion cyclotron frequency and plasma frequency respectively, A is the anisotropy of the energetic particles, L is the length of the region in which waves are amplified and R is the "reflection coefficient" which determines the fraction of emitted wave amplitude which returns to the amplifying region, and V_R is the resonance (parallel) velocity of the protons. For roughly estimating the number density and energy density of trapped protons, if these were determined by the limit given above, one can use a proton velocity distribution which is equal to the limit given above between some $V_{R\,max}$ and $V_{R\,min}$, but zero outside these limits. The number density, obtained by integrating $F_{max}(V_R)$ with respect to V_R, will then depend primarily on $V_{R\,min}$, while the estimate of energy, obtainted by integrating $V_R^2\ F_{max}(V_R)$ will depend primarily on $V_{R\,max}$.

The number density of energetic protons then reduces to

$$N_{EP} \simeq 3.10^4\ c\ \log \left(\frac{1}{R}\right)\left(\frac{1}{A}\right)\left[\left(\frac{1}{V_{R\,min}}\right) - \left(\frac{1}{V_{R\,max}}\right)\right]^B$$

where B is in gauss, while the proton energy density W_{EP} is given roughly by $W_{EP} \simeq 3/2m\ V_{R\,max} V_{R\,min}\ N_{EP}$. For a surface field of 10 gauss, and a value of μ of 100 MeV per gauss, the mean energetic proton energy at L=7 would be 3 MeV so that the mean resonance velocity is about c/100. If we take a minimum value of c/100 and a maximum of c/50, we get an upper limit to the number of energetic protons. Using log (1/R) = 3, A=1, B=1/35 gauss we obtain

$$N_{EP} \simeq 3.10^5/m^3 = 0.1/cm^3$$

Then energy density would be about 3.10^5 MeV/m^3 or 5.10^{-8} Joules/m^3. The magnetic field energy density is about 3.10^{-6} Joules/m^3, so that the ratio of these, which is the β of the protons, is about 10^{-2} at an L value of about 7. At smaller distances, if the protons are diffused in, we would expect β to be roughly constant, until very near the planet when atmospheric losses become important. The above value represents a reasonably safe upper limit to the proton number densities and energies, but an upper limit which gives proton energy densities much, much larger than those of the electrons. In fact, there is no very obvious reason why the protons should have energies more than about 5 times those of the electrons in the region where synchrotron emission is not having a major influence on the electron energy and density, and the number densities of energetic protons in this region are most probably about the same as those of the electrons. Thus, a "best guess" at the proton number density and energy density equal to and 5 times that of the electrons respectively at about L-3, with the proton number density and energy increasing roughly as L^{-3} inside this point.

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DISCUSSION

DR. MEAD: Does your diffusion mechanism imply that for the Earth, protons can come in to L=2 in times like 100 hours?

DR. BRICE: If the spectrum of the perturbations in the electric field are very closely matched to the proton drift period.

DR. SMITH: This is a resonance.

DR. BRICE: It is not pure resonance, in that this ins't the minimum time. If the protons picked up the maximum potential every time, then you get things that are quicker than this. A very closely peaked power spectrum yields this order of magnitude. The point is that there is an enormous difference between Earth and Jupiter, and the electric field here is much weaker than for Jupiter. Also, each time you go around in orbit, you pick up some pieces of potential across the orbit, and to get up to 100 MeV takes many, many orbits when the potential across the orbit is only a few kV, whereas to get up to 500keV is much faster. This says that the diffusion gets very, very slow as you come in.

DR. THORNE: Why do you use 1,000 hours for the drift time rather than the 10-hour corotation time of Jupiter?

DR. BRICE: I combined the two. What you end up with is essentially the drift time for Earth and essentially the corotation time for Jupiter. Thus, I did use 10 hours for Jupiter.

DR. BEARD: You gave an estimate that the proton energy density would be about ten times the electron energy density. Would you say any more about that estimate if you take into account the rapid loss in energy of the electrons?

DR. BRICE: That is a very good point. In the region where β is increasing quite rapidly for the electrons and where it is clear that the synchrotron radiation is not drastically reducing the fluxes, that you would simply multiply by a factor of 10. If you continue to diffuse the protons in and the density goes roughly as L^{-4} and the energy goes like $L^{-8/3}$, and the energy density in the particles, if you simply interchange the flux tubes, very quickly would go like $L^{-20/3}$, and the magnetic energy density goes like L^{-6}. I think that if there are any loss processes, you could maintain a constant β, that is the ratio of the energy in the particles to the energy in the fields. When β starts falling off, just keep on coming in at constant β, and I think that is the best guess you have for the protons.

DR. THORNE: Did I understand you right when you said number density of the electrons should be the same as the number of protons, rather than the fluxes being constant? The stable trapping limit is the same.

DR. BRICE: I looked into the stable trapping limit, and that gives $\beta=10^{-1}$, whereas ten times the electron β is 10^{-3}. I agrue that there is some other process which is wiping out the electrons and the protons and reducing β. This process may be interchange at the boundary. The boundary is a very tough question, because you have got particle corotation energies of kV and thermal energies like 10V. I don't know what happens when they try to mix with the solar wind where the thermal energy is very large and the drift velocity is not so large.

DR. THORNE: You are making an *ad hoc* assumption that β stays the same?

DR. BRICE: β might go as $L^{-2/3}$ or something, but it shouldn't change very much.

DR. WHITE: Even where β=0.1?

DR. BRICE: I said if you look at the stable trapping limit that comes about from the fluxes of the electrons, you get $\beta \simeq 0.1$. That, I think, sets an upper limit that you can have a lot of confidence in. I would be extremely surprised if you got a β much larger than 0.1 at L=7. Very conservatively it will increase as $L^{-2/3}$, or something, as you come in. I think that a much more realistic estimate is to take the electron β and then say that the proton energy is, perhaps, 10 times higher than the electrons.

DR. MEAD: Where does that magic number of 10 come from?

DR. BRICE: If you look at the energies behind the shock, the protons are like 1 keV, and the electrons like 200 eV.

DR. MEAD: And where do the constant densities come from?

DR. BRICE: If you take a piece of magnetic field in the solar wind with protons and electrons on it and then bring it all the way in, the densities will be about the same for the electrons and the protons.

DR. WARWICK: That is exactly what I did.

DR. MEAD: You are talking about fluxes?

DR. WARWICK: No. I was talking about protons with solar wind energies and the same density as the electrons in the solar wind. Then using L-shell diffusion I got 29 MeV at the peak of the belts.

DR. BRICE: Right; and about five times that for the protons, and the number densities will be about the same.

DR. BEARD: Isn't it true that 200 eV for electrons will not give you 40 or 50 MeV electrons at L=2?

DR. BRICE: Well, a kilovolt in the solar wind gives you 100 MeV/gauss as a magnetic moment. When you come in to L=2, you have about 100 MeV protons.

DR. WARWICK: For the electrons 6.2 MeV at L=1.8 corresponds to 180 eV outside the magnetopause. That is exactly the computation I get.

DR. BRICE: I won't argue factors of five.

DR. WARWICK: Neither would I.

DR. BRICE: I think the electrons could have 50 keV, but Dr. Beard's original calculations where you had electrons at 700 MeV/gauss had me really scared.

DR. WARWICK: The number that I quoted was an interpolation. In other words, I concluded that the energy of the electrons was 6 MeV from the same data.

DR. BEARD: I was concluding about 70 MeV at L=3.5 from the radio observations.

DR. WARWICK: An then, I concluded that the electrons energy at the magnetopause was 180 eV, which seemed to me about right. It seemed to me a confirmation of the low energy which I already believed on the basis of the decimetric radiation.

DR. BRICE: If that is an accident, it is a pretty tough accident to take. Otherwise, you have to argue that the electrons come in from the solar wind, conserving the first two invariants.

DR. WARWICK: That is exactly what I concluded.

DR. HESS: If you have any trouble getting the electrons in the first distance and you are having an interchange instability, take the thermals out.

DR. BRICE: The interchange instability is simply going to interchange flux tubes, and that will conserve the first two invariants.

DR. HESS: But you have to put the total energy into that and to decide, also, which two tubes move outward. Is it obvious that the thermals dominate the total energy?

DR. BRICE: Beyond an L of 7 (R_J), yes; because the energy to be gained by the thermals going out is about 10^{11} watts. The total energy you are getting, about that of the synchrotron radiation, is 10^9 watts; in other words, what we are saying is it takes 10^9 watts to get the particles into L=2, so it obviously takes substantially less than that to get them in to L=7, because most of the energization takes place close in. There is available a source of energy 2 orders of mangitude larger, at least, to get them in to L=7. I can't see any way to get them in to L=1.5. For this, you have to use a mechanism which is going to be very effective at low L values and which has an energy source associated with it like 10^9 watts. The real hooker comes from getting them from L=3 to L=1.5.

DR. HESS: Do you have an ionospheric dynamo model that will give an L dependence or any kind of rates?

DR. THORNE: Could I throw one other mechanism in? There is evidence that the atmosphere of the planet rotates differentially as a function of latitude.

DR. BRICE: There is without question lots of turbulence in the atmosphere, but whether gravity or other waves can take up energies like 10^{11} or 10^{12} W into the ionosphere is a question. That is rather more than we get on the Earth. The differential rotation evidence says that there is likely to be more turbulence on Jupiter. I don't really have any serious problem living with that mechanism. I have very great difficulty living with the electrons without that.

DR. DIVINE: Is it true in the cases of low conductivity ranges and low diffusion times for the field through the satellites, that they will carry their flux tubes with them, depending on the ratio of the integrated conductivity across the satellites to that across the ionosphere? If that is the case, then you have a mechanism for magnetic disturbances within that range of the magnetosphere where the satellites are.

DR. BRICE: The total energy associated with Io, which is clearly going to be the biggest hammer in this, is like 10^{11} W. Nearly all of this will be dissipated in the ionosphere or in the 10 kV electrons that get accelerated by Io to carry the current. I have an incredible time getting 10^{9} W in the decametric radiation, which is believed to be tied to the foot of the field line. And I find it much more difficult to get this into the decametric radiation; we are going to have 1% conversion from a wave with a period of 10 hours to a wave with a frequency of 30 MHz. It is very rough to do so right at the foot of the field line. It is very difficult for Io at 6 R_J to have 1% of its energy go into diffusing particles at L=2 or 1½. That energy source has got to be able to provide energies like 10^{11} or 10^{12} W at L values of 1½ or 2. This has got to be a big energy source.

DR. SMITH: I want to get a clarification of your idea about the photoelectrons coming out of the ionosphere since there's no thermal plasma, at least initially.

DR. BRICE: We said that the photoelectrons are going to go out there and due to the stringent instability of scattering, the magnetic field will trap a few of them in the equatorial plane. Then we will have a potential drop along the field line, and that potential drop will build up until the protons get out there. The flux of the protons is equal to the flux of electrons, and that will happen when the potential drop on the field line is equal to the energy required to lift the proton up. If it takes 5 V to get a proton up to this potential barrier, then I have to have a 5 V (give or take a tenth of a volt or a hundredth of a volt) potential drop along the flux tube to get the proton up to that point. That potential is going to slow down the electrons by 5 V, so we took the electron energy and took out 5 V or 10 V, or whatever it required to pull the proton up, and said that is the potential drop along the field line. Then we calculated how many electrons will escape if all electrons less than 5 V don't escape. So we did take it into account in figuring out the flux.

DR. SMITH: You have to use different energies to get them up, I guess, because of the different proton and electron masses. I guess that comes out.

DR. BRICE: The energy required to take the particles up against the gravitational field is 10 eV for the protons and 0.002 eV for the electrons.

DR. GULKIS: Did I understand your figure 4 correctly, that the density goes up to 100 cm^{-3} and stays that way for several radii?

DR. BRICE: Yes, near L=7.

DR. GULKIS: Now, I want to know what Faraday rotation you expect in that region, say through 2 Jovian radii.

DR. BRICE: At L=7 or 8, the field is a lot weaker than it is at L=2, by a factor like 64.

DR. WARWICK: That is taken in, though.

DR. BRICE: And you had 10 cm^{-3} at L=2, so I think you can have it 64 times larger, which is 600 cm^{-3}.

The other thing is that if the decametric radiation comes from the foot of Io's flux tube and goes out in the ecliptic plane, it is going to be off the equator by almost a Jupiter radius. The density there, according to our model, will be down by a factor of e or so. In computing the temperature, we took the energy of the escaping electrons and assumed that it all went into thermal energy, and that none of it got down into the ionosphere. In this outermost region, we have temperatures of roughly 10^{5} °K, which is probably too high. If there is any conductivity down to the 150-degree ionosphere the temperature will be cooler. Then the scale height around the equatorial plane will be less, and the plasma will be more closely confined to the equatorial plane. So it is conceivable that you could have a blob of plasma 1/10th an R_J wide in the equatorial plane and that the emission would bypass it. However, even if that doesn't happen, I believe that my numbers are consistent with Dr. Warwick's. I don't think I could argue for more than 10^3 cm^{-3} at L=7 instead of 10^2 cm^{-3}.

DR. WARWICK: I compute that at L=7, for a path length of $3R_J$, the upper limit would be 10^4 cm^{-3}. Your number is well within that.

DR. BRICE: I could push it up to 10^3 cm^{-3} on the basis of the physics, but I wouldn't like to put it any higher than that. Thus, the present numbers don't conflict.

DR. BEARD: Dr. Brice, do I understand correctly that your model has photoelectrons being injected and then trapped? What is the energy of the photoelectrons at the position they are trapped, roughly?

DR. BRICE: It is the energy that they start off with less the energy required to get over the barrier, 30 V minus 5 V, namely about 20 V.

DR. BEARD: It is this space charge communicated along the field line that drags the protons up. How much spread would there be in the electrons due to the space charge that they are building up?

DR. BRICE: What do you mean?

DR. BEARD: If you have got a collection of electrons as a potential source, then the electrons would be spread out along the field line because of the space charge.

DR. BRICE: No. The numbers of electrons and protons are essentially equal, and the fluxes are essentially equal. The total difference in the densities integrated along the flux tube is enough to give you 5 V required to pull up the protons.

DR. SMITH: One of the things that worries me is the absence of a magnetopause. I can't think of any examples where the solar wind likes to mix with other kinds of plasma. It seems to like to make sharp boundaries, based on our experience near 1 AU.

DR. BRICE: That is exactly what it is going to do as long as it comes into a region where the magnetic field energy density dominates the particle energy density, which occurs at the Earth's magnetopause. In Jupiter's case, I maintain that the energy density in the particles is likely to be larger than the energy density in the magnetic field, so that the magnetic field does not control whatever is going on. The solar wind velocity at Earth is orders of magnitude bigger than the corotational velocity at the boundaries. At Jupiter it is smaller. Because I come up with very stupid answers just scaling things, I am very reluctant to do so when I know that there is a nondimensional parameter which is larger than one in one case, and smaller than one in the other.

DR. CORONITI: I think there is good evidence for that in the Earth's magnetosphere. I have seen crossings of what you would call the magnetopause boundary in which the Earth's magnetic field dropped by a factor of 2 or 3, indicating a very, very high β for the inside region. It was very difficult to tell where you were, whether you were inside or outside or whether it was a boundary or anything at all.

DR. WARWICK: I would like again to stress that if you consider what power Io generates in Alfven waves the principal conductivity of Io is an important unknown, which might range anywhere over 6 orders of magnitude. But within that range there is a sufficient conductivity to generate considerable power in Alfven waves.

DR. BRICE: Even 10^{11} watts?

DR. WARWICK: Much more than 10^{11} watts.

DR. BRICE: Goldreich would argue that the Alfven waves are driving the electrons that radiate.

DR. WARWICK: No, he doesn't. His argument on Alfven waves is simply to show that they set a limit on the timing of the problem. If there isn't enough time for an Alfven wave to run along this DC path, then the DC path doesn't exist, but if there is enough time, then we have a DC path and a conductivity argument that is pertinent.

DR. BRICE: I don't think we do quite have a DC path, because if you look just above the ionosphere, the density of the electrons is so low that in order to carry the current, they would have to travel at velocities near the velocity of light.

DR. WARWICK: That is exactly how he gets the energies of the electrons in his model.

DR. BRICE: In my model, I simply take the perpendicular energy at Io, which is a thermal energy about 10 or 20 eV and conserve the magnetic moment as I come in to higher energies at small L values.

CALCULATION OF NEUTRON-DECAY-PROTON TRAPPING IN THE JOVIAN MAGNETOSPHERE

J. R. Thomas and W. R. Doherty*

INTRODUCTION

There is considerable uncertainty in estimates of the proton fluxes trapped in the Jovian magnetosphere. Direct experimental evidence on these fluxes is extremely difficult to obtain remotely (i.e., from Earth) essentially for the following reasons:

1) Protons are too massive to radiate significant synchrotron radiation in comparison with electrons of comparable rigidity.
2) Direct interactions of energetic protons with the satellites produce very few escaping photons. The fluxes of protons with energies from 10 keV to 10 MeV may be high enough to produce auroral displays on Jupiter.
3) Protons, again because of their mass, have relatively little influence (compared to the electrons) on high frequency waves propagating through a plasma.

Furthermore, there are still many incomplete points in our understanding of the Earth's Van Allen belts. Thus, a complete theoretical solution of the source and loss mechanisms around Jupiter has not yet been attempted. A slight additional complication is that radio data still leave some uncertainty in the strength and configuration of the Jovian magnetic field, although this uncertainty is probably small compared to many other factors that govern the proton source and loss mechanism.

*The Boeing Company, Aerospace Group, Research and Engineering Division, Seattle, Washington 98124

Our study of the Jovian radiation belts began in 1967 with a look at the implications of the synchrotron radiation mechanism and an attempt to bound the proton flux. In this latter regard we have explored as time permitted the possible proton fluxes resulting from cosmic ray albedo neutron decay (CRAND). We present the main points of that work here.

As general background, we recall that experimental data on the Earth's belts are still reasonably consistent with a cosmic ray albedo neutron decay (CRAND) source for most of the protons with energies in excess of 50 MeV in the heart ($1.2 \leq L \leq 2.5$) of the inner belt (Freden, 1969; Schardt and Opp, 1969). (We use L for the McIlwain parameter, that is, the equatorial radius of the field line in units of the <u>planet's</u> radius, for either the Earth or Jupiter; and thus the length scale factor is determined by the context.) We assume that the number of albedo neutrons created by the cosmic ray flux on the Jovian atmosphere is the same per incident cosmic ray particle as at Earth (Lingenfelter, et al. 1965a) and we assume the cosmic ray flux and spectrum incident on the Jovian magnetosphere is the same as on the Earth's magnetosphere. The significant difference then is in the fact that considerably higher-energy particles are needed to reach the atmosphere of Jupiter at the same magnetic latitude.

Next, from a geometrical calculation, we derive the ratio of the CRAND source averaged over an L shell on Jupiter to that on Earth at L=1.3. We also discuss the ratio of average loss rate on Jupiter to that for the Earth. We then <u>assume</u> that all of the earth's inner belt at L≈1.25 to 1.3 is due to CRAND. Since the equilibrium flux is given by the source intensity divided by the loss rate, we obtain the flux around Jupiter by scaling according to the ratio of source to loss from the flux observed in the heart of the inner belt.

Basic Data

Review papers by Warwick (1967 and 1970) and by Carr and Gulkis (1969) describe the radio emissions from Jupiter in some detail. Our knowledge of the magnetosphere today must be deduced from these measurements. Briefly, the combination of decimeter (synchrotron) radiation data and decameter burst data allow deduction of the surface magnetic field to within a factor of about 2. For example, Warwick (1967) cites 10 ± 5 gauss, but in his 1970 work gives a best value for the magnetic moment of Jupiter of $2.5(10^{30})$ gauss cm^3. This moment corresponds to a field of 7 G on the magnetic equator (or 14 gauss at the pole).

Deductions of the flux of radiating electrons are also fairly well established (within an order of magnitude at least). Other quantities are much less certain. Scarf (1969) presents some reasoning that adiabatic solar wind flow extends to Jupiter. Hence, the following description of the boundary of the Jovian magnetosphere is generally accepted. The picture is an analog of the Earth's magnetic cavity in the solar wind. The extent in the solar direction is determined essentially by a balance between planetary magnetic field pressure and solar wind pressure (Beard, 1960). For Jupiter, the velocity of rotation should also be taken into account. With the usual Scarf (1969) wind density dependence of inverse distance squared and constant velocity, Brice and Ioannidis (1970) calculate the bow distance to vary between 26 R_J and 53 R_J with, of course, some time variation depending on the solar wind. Hence, regions of the magnetosphere out to $L \sim 20$ are quite deep inside the magnetosphere and long-duration magnetic trapping appears possible inside this region.

Magnetic Field

For the purposes of the CRAND calculations, we have adopted a centered dipole field with a magnitude on the surface at the equator of $B_S = 6$ gauss. Nondipole terms in the main field become less important at larger distances and are thus justifiably neglected over most of the region of interest (to 20 jovian radii). A more significant problem might be time dependent perturbations in the field, but without better knowledge of the time variation, we ignore its great possible complication in this first treatment. (Some discussion of possible loss mechanisms due to magnetic waves is included below).

Cutoff Rigidity[*]

Two kinds of cutoff rigidity enter the CRAND calculation in a significant fashion.

They are:

1) The trapping cutoff rigidity P_c^T. For greater rigidity, first adiabatic invariant is not conserved (i.e., nonadiabaticity).
2) The vertical cutoff rigidity P_c^V of a dipole field. As a function of magnetic latitude, particles of lower rigidity coming from large distances in a dipole field are prevented from reaching the surface (of a sphere) over half of the 2 π outwards direction (i.e., π steradians).

Both of these cutoffs scale as $B_s R_s$ at a given L value in a dipole field, where B_s is the surface field and R_s the radius of the planet. Both are evaluated here for the model jovian magnetosphere. We emphasize that these quantities are of some importance independent of the CRAND model. That is, 1) the trapping cutoff provides an upper energy cutoff for individual trapped particles in any model, and 2) the vertical cutoff provides a local measure of magnetic shielding from charged particles arriving from outside the magnetosphere.

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*Rigidity is momentum per unit charge

Trapping cutoff (i.e., breakdown of the first adiabatic invariant) occurs when the radius of gyration $r_g = P_\perp/(cB)$ ($P_\perp$ = perpendicular component of rigidity in volts, other quantities in MKSA) exceeds a critical fraction η of the characteristic length $\ell = B/|\nabla B|$ associated with the spatial variation of the magnetic field. In a dipole field, centered and aligned with a spherical (r,θ,ψ) coordinate system

$$\frac{|\nabla B|}{B} = \frac{3}{r}\sqrt{1 + \frac{\cos^2\theta \sin^2\theta}{(1 + 3\cos^2\theta)^2}}$$

or

$$1 \leq \frac{r|\nabla B|}{3B} \leq 1.0541 \quad .$$

Hence, the characteristic length ℓ is nearly independent of altitude and

$$\ell \sim \frac{r}{3} \quad .$$

The radius of gyration is a maximum in the equatorial plane for a given particle orbit. (This theorem is evident from 1) the constancy of the first adiabatic invariant, which is proportional to $P_\perp^2/B$, so that $r_g \propto 1/\sqrt{B}$, and 2) the equatorial location of the position of minimum B along a given field line.) Therefore, the criterion for breakdown of trapping should be evaluated in the equatorial plane.

In the fashion now customary for the geomagnetic field, let $r=LR_0$ where R_0 = radius of the planet and L is the magnetic shell parameter (McIlwain parameter), which measures equatorial distance to a field line in units of R_0. Again in the equatorial plane where $B=B_0/L^3$ with B_0 being the equatorial surface field, then

$$\frac{r_g}{\ell} = \frac{P_\perp}{cB}\,\frac{|\nabla B|}{B} = \frac{3P_\perp L^2}{cB_0R_0} \quad .$$

We assume that the critical value η of this ratio at cutoff may be evaluated from data on the Earth's inner belt. Figure 1 shows data from the composite flux maps of Vette, which does verify the $1/L^2$ dependence of the cutoff rigidity for a given planet.

From this data, we find

$$\eta \simeq \frac{1}{8} \quad .$$

Then

$$P_c^T = \eta\,\frac{c}{3}\,\frac{B_0R_0}{L^2} \quad . \tag{1}$$

Thus, from planet to planet, the trapping cutoff rigidity scales as B_0R_0 at a given L value. For example, the Jovian belts can hold as rigid a spectrum as that at the heart of the inner Van Allen belt (L_e=1.3) on the field line through

$$L_J = 1.3\sqrt{\frac{R_JB_J}{R_eB_e}} \simeq 18 \quad . \tag{2}$$

Fermi (1950) derives the cutoff rigidity for particles incident from a large distance to reach a certain radius R_0 in a magnetic dipole. The vertical cutoff [i.e., particles of this rigidity can reach the point specified by (R_0,λ) over only half of the total 4π solid angle, and the flux at

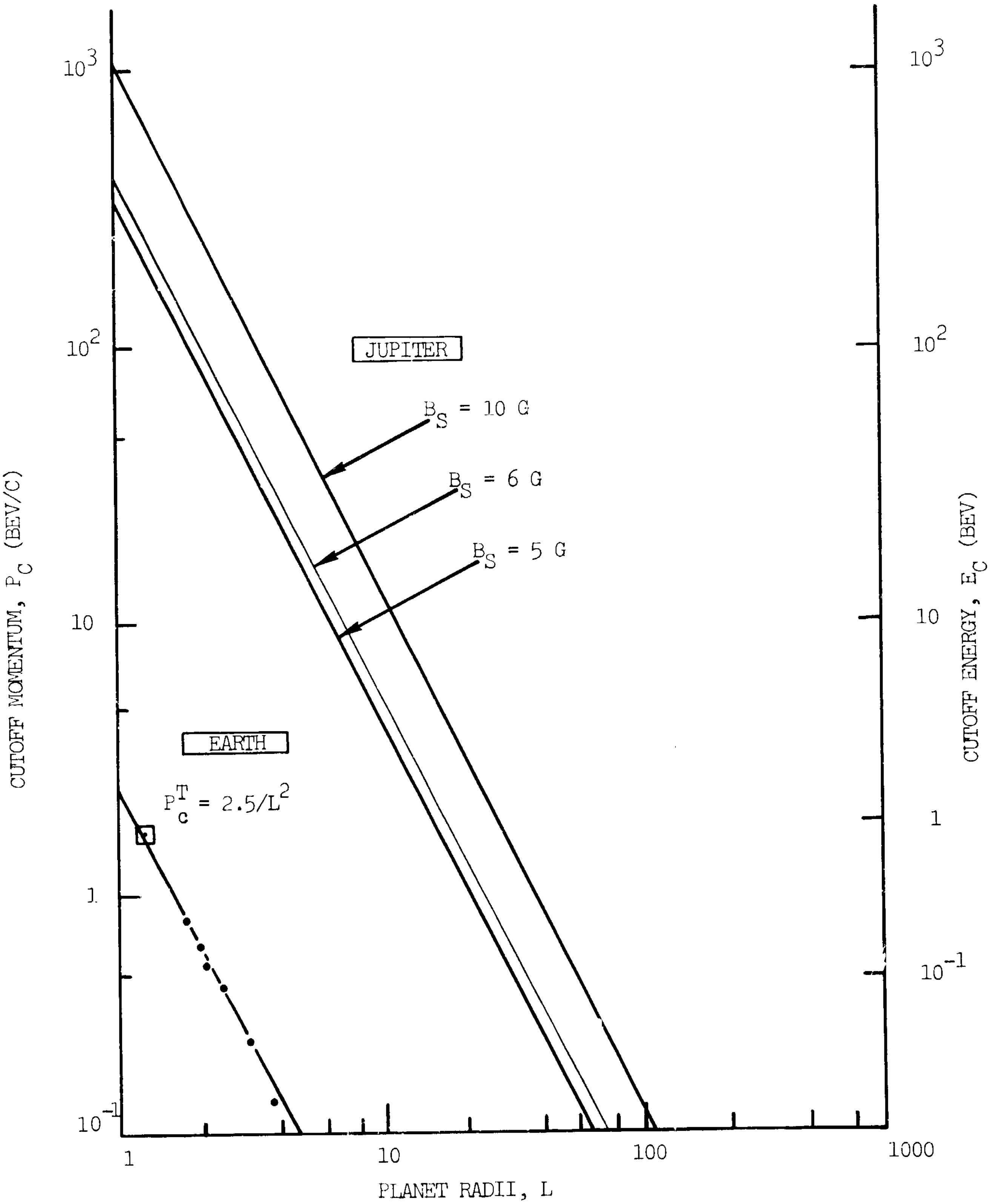


Figure 1. Trapping Cutoff Rigidity

this energy is thereby reduced by a factor of 2 (with planetary shadowing neglected) from its incident value at large distance] may be expressed as

$$P_c^V = \frac{1}{4} c\, B_o R_o \cos^4\lambda \qquad \text{(MKSA, } P_c^V \text{ in volts)}$$

where B_o is the equatorial value of the field at radius R_o, and λ is the magnetic latitude. For the Earth, the resulting vertical cutoff is the well known

$$P_c^V = 14.9\ (10^9)\ \cos^4\lambda \qquad \text{volts} \tag{3}$$

This dipole calculation does not take into account details of the Earth's field (Shea and Smart, 1967; Reid and Sauer, 1967) or solar storm effects (Bingham and Webber, 1967) that are particularly important at high latitudes ($\lambda > 65°$). By comparison, the jovian vertical cutoff at the approximate cloud top radius $R_J = 11R_E \approx 71(10^3)$ km (cf, Michaux, 1967; Dollfus, 1970) is with the adopted equatorial value there of 6 gauss,

$$P_c^V\ \text{(Jupiter)} = 210\ P_c^V\ \text{(Earth)}$$

$$= (3.13\text{x}10^{12})\ \cos^4\lambda \qquad \text{volts} \tag{4}$$

In other words, the consequence of Equation 4 is that cosmic ray protons in the 15 to 300 GeV range, which have nearly unimpeded access to the Earth's surface, are restricted (depending somewhat on energy) to the magnetic polar regions of Jupiter.

Sources of Neutrons

Three neutron origins have been considered in Earth magnetospheric physics as possible sources of energetic decay protons. These three are:

1) cosmic ray albedo neutrons
2) solar proton albedo neutrons
3) solar neutrons

Solar protons have been shown quite conclusively (Lenchek, 1966; Freden, 1969) to be an insignificant factor in producing energetic albedo neutrons around Earth. These will be even less significant at Jupiter because:

1) their flux is reduced relative to the cosmic ray flux at Jupiter by an inverse square of the distance from the sun ($\sim 1/(5.2)^2$)

2) the large vertical cutoff rigidity of the jovian field (eq. 4) reduces the accessible (polar) area of the jovian atmosphere to essentially zero for these protons (energies $\lesssim 1$ GeV).

Hence, further considerations are restricted to cosmic ray albedo neutron decay (CRAND) and solar neutron decay (SND).

CRAND Injection

We consider here the CRAND source of protons in the energy range $E \geq E_{ND} \sim 50$ to 100 MeV but with $E \leq E_c$, where E_c is the trapping cutoff. Typically, we use the trapping cutoff energy of the Earth at L=1.3 or of Jupiter at L=18, where E_c=800 MeV. Note that for a particle of charge ±e

$$E_c = -Mc^2 + \sqrt{\left(eP_c^T\right)^2 + M^2c^4} \longrightarrow \begin{cases} eP_c^T & \text{ultrarelativistic limit} \\ 1/2\dfrac{\left(eP_c^T\right)^2}{Mc^2} & \text{nonrelativistic limit} \end{cases}$$

We follow the basic method of Lenchek and Singer (1963) in evaluating the injection rate. However, the case to be considered here is a cross between their "global" component generated over the whole Earth by the galactic cosmic rays and the "polar" component (generated in the polar regions by solar cosmic rays). On Jupiter, the galactic cosmic rays of interest are restricted to the polar regions, but produce energetic albedo neutrons and hence a distribution of decay protons that, at injection, retain the direction of the neutron. In the approximation of Lenchek and Singer to be used here, the neutrons in the energy range of interest are produced isotropically within a cone of half angle $\bar{\theta}(E)$, where

$$\sin\bar{\theta} = \frac{300}{P} \qquad P = \text{momentum of neutron in } \frac{\text{MeV}}{c} \tag{5}$$

about the direction of the incident cosmic ray. For such a neutron to escape the atmosphere, the proton must have, therefore, been traveling within an angle $\bar{\theta}$ of being tangent to the atmosphere. Furthermore, the albedo neutrons are restricted to angles within $\bar{\theta}$ of being tangent to the atmosphere.

To describe the geometry of the injection in detail, we introduce two cones, called in the terminology of Lenchek and Singer, the α-cone and the δ-cone, shown in Figure 2, each with its vertex at some point (R,λ) that represents the guiding center of a set of trapped proton trajectories. From this point, the velocity directions of particles of a given pitch angle α form the α-cone and the δ-cone is that subtended by the planet; i.e., the locus of rays drawn tangent to the planet. If albedo neutrons are restricted to angles within $\bar{\theta}$ of being tangent to the atmosphere, then injection must come from a range of directions inside the δ-cone that do not form an angle of less than $\pi/2 - \bar{\theta}$ with the local zenith to the planet surface. The half angle of the δ-cone is given by

$$\sin\delta = \frac{1}{R} \tag{6}$$

in units where planetary radius = 1. In this case, $R = L\cos^2\lambda$ where L is the standard McIlwain shell parameter.

The conical surface of rays making an angle ϕ with the zenith is inside and coaxial with the δ-cone. Its half angle is δ' where

$$\sin\delta' = \sin\delta \sin\phi$$

The minimum value of δ at which injection occurs is then given by

$$\sin\delta_1 = \sin\delta \cos\bar{\theta} \tag{7}$$

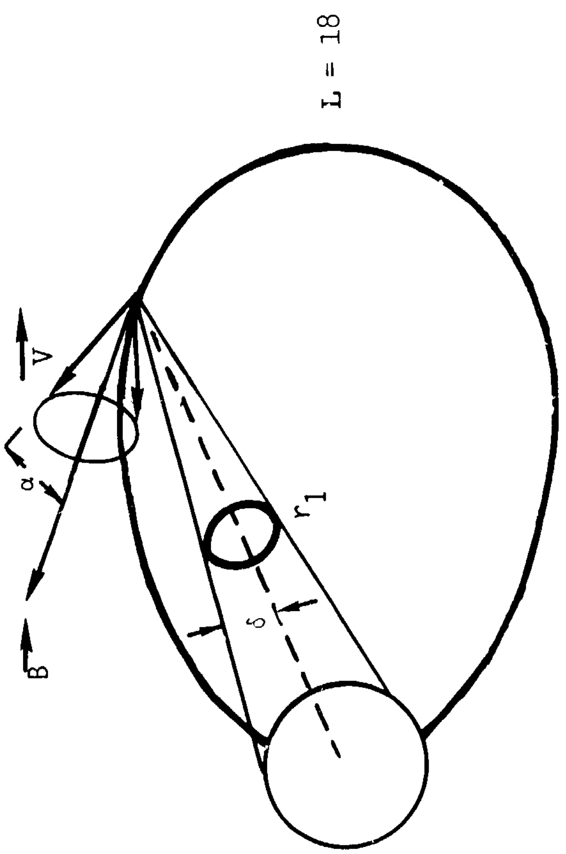


Figure 2. Geometry of Injection at Jupiter

Exact solution of the injection problem would require evaluation of the range $\Delta\psi$ in phase angle of gyration at each latitude λ over which injection can occur for some pitch angle $\alpha = \alpha(\alpha_0, \lambda)$ where α_0 is the equatorial pitch angle for a proton on the specified orbit. That is, from conservation of the first adiabatic invariant,

$$\frac{\sin^2\alpha}{B(\lambda)} = \frac{\sin^2\alpha_0}{B_0}$$

or

$$\sin^2\alpha = \sin^2\alpha_0 \frac{\cos^6\lambda}{\sqrt{1 + 3\sin^2\lambda}} \tag{8}$$

Then, integration of the injection range over λ with α varying in accordance with equation 8 gives the total injection into pitch angle α_0. Finally, an integration over all pitch angles would give the total injection rate. This detail is required to solve for the equilibrium flux in a model where the diffusion rates and loss rates are known as a function of pitch angle and position. However, we have not considered such a detailed loss mechanism. Hence, for our purposes here, we evaluate just the total injection rate without keeping track of the pitch angle at which injection occurred.

We check first that the injection occurs outside the loss cone; i.e., the range of pitch angles for which the trajectory would immediately lead to altitudes near the surface. At the given point (R, λ) in space, Figure 3 shows that injection by a neutron leaving the planetary surface at <u>any</u> angle can occur only over a range of pitch angles such that

$$|\beta - \delta| = \alpha^- \leq \alpha \leq \alpha^+ = \beta + \delta \tag{9}$$

where β is the angle between the radius vector and the $\bar{B}$ vector. In dipole coordinates

$$\cos\beta = 2\sin\lambda / \sqrt{1 + 3\sin^2\lambda}$$

or

$$\tan\beta = \text{ctn}\,\lambda/2 \tag{10}$$

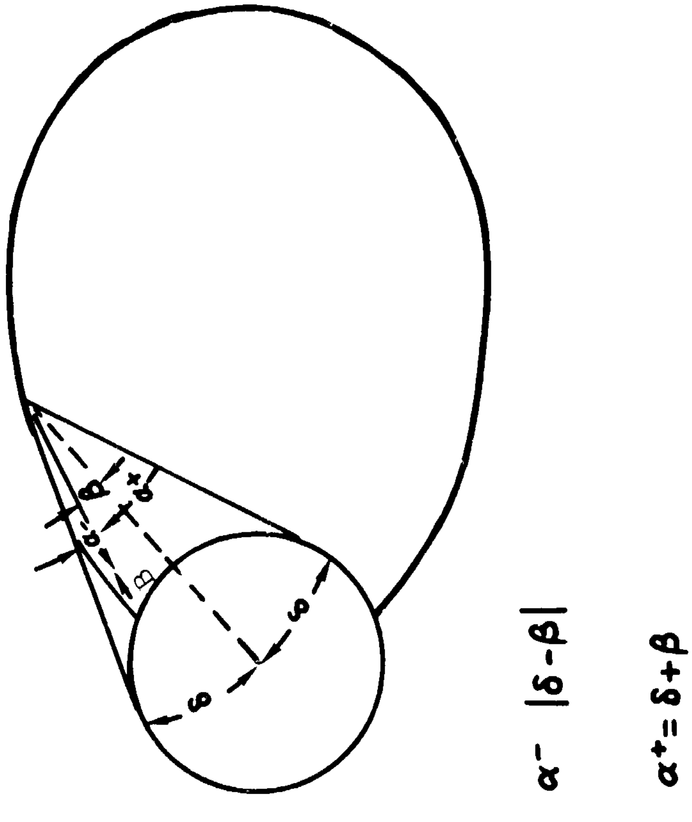


Figure 3. Limits on Pitch Angle at Injection

Negative values of α^- imply injection occurs from regions surrounding the point where the tangent to the field line intersects the planetary surface and therefore includes the direction parallel to the field. The limits $\alpha_0^{\pm}$ on the equatorial pitch angles due to injection at latitude λ on a given L shell are obtained by taking the sine of the equations for the upper and lower limits on the right and left of equation 9, by employing equations 6 and 10 to exp· ·s β and δ in terms of L and λ, and by converting the result to equatorial angles with equation 8. The equation so obtained is

$$\sin\alpha_0^{\pm} = \frac{\cos^2\lambda \sqrt{L^2\cos^4\lambda - 1} \pm \sin 2\lambda}{L\left(1 + 3\sin^2\lambda\right)^{3/4}} \tag{11}$$

The values of α_0^+ and α_0^- along the field line L=18 are plotted in Figure 4. Note that the equatorial loss cone at L=18 is given by

$$\sin\alpha_L = \frac{\cos^3\lambda_0}{\left(1 + 3\sin^2\lambda_0\right)^{1/4}} = \frac{\left(\frac{1}{18}\right)^{3/2}}{\left(4 - \frac{3}{18}\right)^{1/4}} = .00937$$

$$\alpha_L = 0.54° \tag{12}$$

The important implication of Figure 4 is that injection along the portion of the field line with $|\lambda| \leq 60°$ does not lie inside the loss cone. We shall use this result in the following calculation.

Comparison of CRAND Injection at the Heart of Earth's Van Allen Belt and at Large L on Jupiter

We now compare average injection rates along a field line. The neutron flux in detail at latitude λ or field line L may be expressed as

$$j_{inj}(E,L,\lambda) \simeq j_n^0(E)\Delta\Omega(L,\lambda)$$

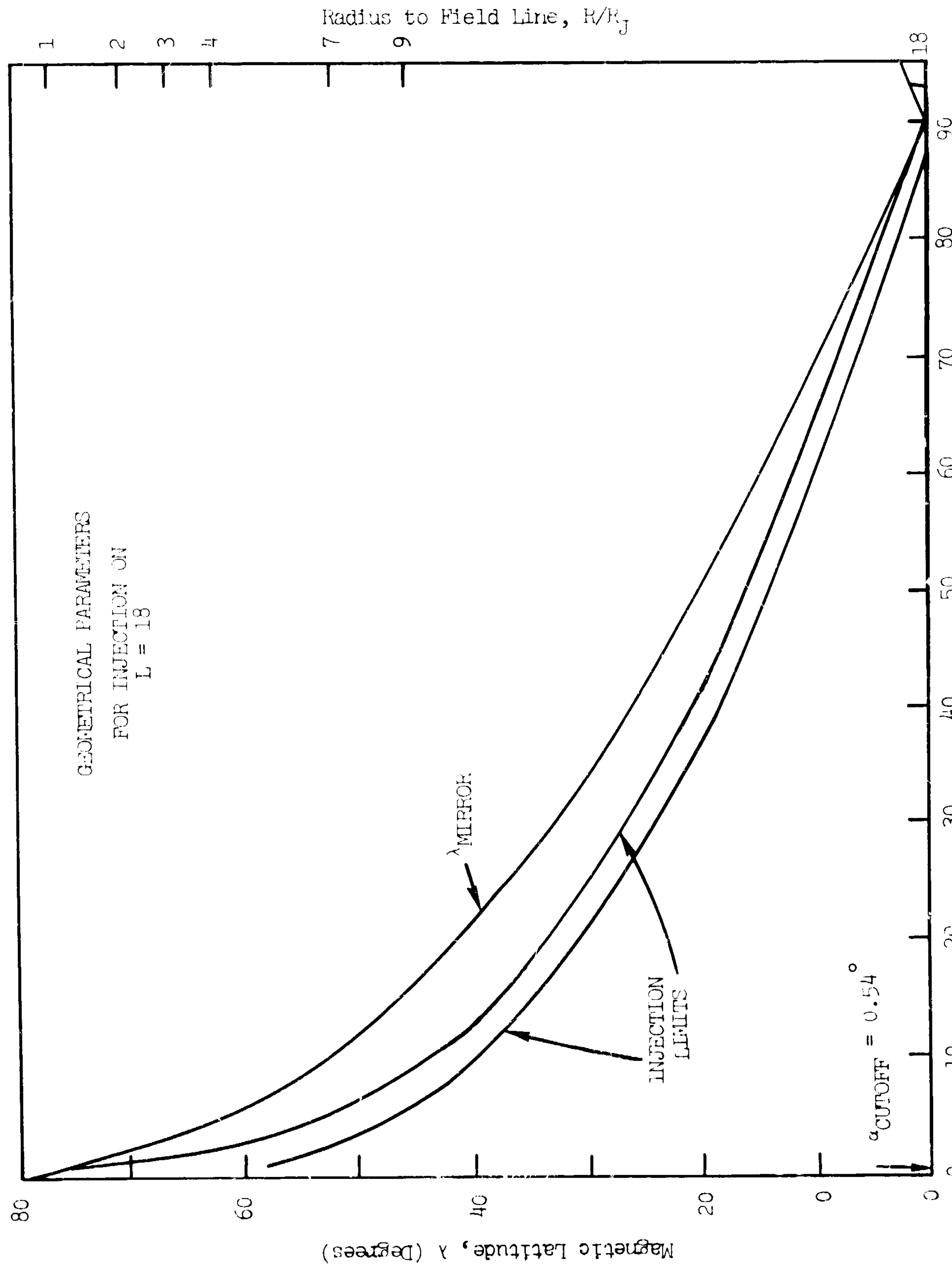


Figure 4. Equatorial Pitch Angle, α_E (Degrees)

where $j_n^o(E)$ is the neutron flux ($cm^{-2}steradians^{-1}MeV^{-1}$) leaving the top of the atmosphere in the region where the appropriate cosmic ray flux can reach the atmosphere, and $\Delta\Omega(L,\lambda)$ is the solid angle subtended by that region about (L,λ). The local injection rate of neutrons is then

$$q_E = \frac{j_{inj}(E)}{\tau_n v}$$

where τ_n is neutron lifetime (including time dilation) and v is the neutron velocity. The average injection rate along a field line is then

$$\bar{q}_E = \frac{1}{s}\int j_{inj}(E,L,\lambda)ds$$

$$\approx \frac{j_n^o(E)}{\tau_n vs} \int \Delta\Omega(L,\lambda)ds \qquad (13)$$

where ds is an element of length along the field line $R = L \cos^2\lambda$. Thus,

$$ds = \sqrt{R^2 + \left(\frac{dR}{d\lambda}\right)^2}\, d\lambda = L\sqrt{1 + 3 \sin^2\lambda}\, \cos\lambda d\lambda$$

and

$$s = \int_0^{\lambda_s} ds = \frac{L}{2}\left[\sqrt{\left(1 - \frac{1}{L}\right)\left(4 - \frac{3}{L}\right)} + \frac{1}{\sqrt{3}}\, \ell n \left(\sqrt{3 - \frac{3}{L}} + \sqrt{4 - \frac{3}{L}}\right)\right]$$

$$s/L \approx 1.380 - 1/L \quad \text{for} \quad L >> 1 \qquad (14)$$

where λ_s is the magnetic latitude at which the particular field line denoted by L intersects the surface of the planet. That is,

$$\lambda_s = \cos^{-1} (1/\sqrt{L})$$

Note that ds is not distance along a spiral orbit (cf, Lenchek and Singer) in our treatment, which does not keep track of pitch angle.

The upper limit on the integral in equation 13 is effectively reduced to the maximum latitude λ_M at which injection does not fall into the the loss cone. This approximation is valid for large L values where the range of injection pitch angles at a given point is small. For field lines in the vicinity of L=18, we take

$$\lambda_M = 60°$$

in accordance with discussion of equations 11 and 12. By symmetry, we have reduced the calculations to one hemisphere only.

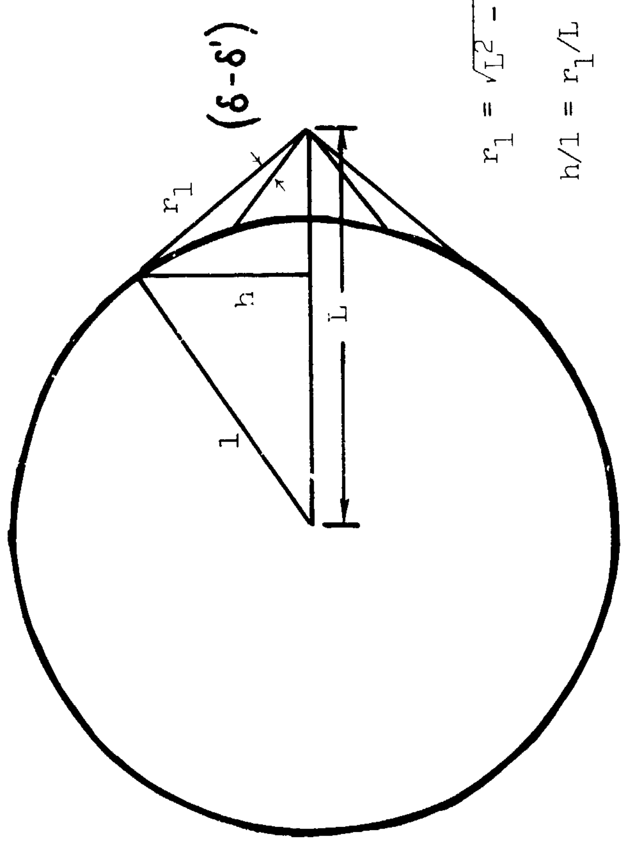
We have assumed that $j_n^o(E)$ is the same at Jupiter and Earth. In this approach $\Delta\Omega$ is in detail a function of energy, but we evaluate it approximately for a typical energy in the 100 MeV to 1 GeV range and use this ratio as a measure of the relative injection rates at Earth and Jupiter. Thus, the average rate over energies of interest in both cases is approximately

$$\bar{q} = \int \bar{q}_E \, dE = (\text{constant}) \, \overline{\Delta\Omega} \tag{15}$$

where $\overline{\Delta\Omega}$ is the average effective solid angle for injection and is evaluated as

$$\overline{\Delta\Omega} = \frac{L}{s}\int_0^{\lambda_M} \Delta\Omega(L,\lambda)\sqrt{1 + 3\sin^2\lambda}\,\cos\lambda\,d\lambda \tag{16}$$

To evaluate $\overline{\Delta\Omega}$ for Earth and Jupiter, we use two different approaches. For the Earth we have a "global" component of incident cosmic rays producing neutrons at angles within $\bar{\theta}$ (eq. 5) of tangent to the top of the atmosphere. For neutron energies between 100 MeV and 1 GeV of interest for the energetic trapped protons, $\bar{\theta}$ = 1/3 radian in the following. Then equatorial injection into the Earth's belt at L=1.3 occurs over the solid angle between the δ'-cone and δ-cone shown in Figure 5, where



$r_1 = \sqrt{L^2 - 1}$

$h/1 = r_1/L$

Figure 5. Geometry of Injection at Earth

$$\sin(\delta-\delta') = \frac{\sqrt{1-\cos^2\bar{\theta}/L^2} - \cos\bar{\theta}\sqrt{1-1/L^2}}{L} = 0.064$$

for L - 1.3.

The effective solid angle for injection at the equator of the earth (injection pitch angles at this location correspond to initial mirroring above the atmosphere) is

$$\Delta\Omega\ (\text{Earth}) \simeq \frac{2\pi h r_1 (\delta - \delta')}{r_1^2} = \frac{2\pi(\delta - \delta')}{L}$$

$$\Delta\Omega\ (\text{Earth}) \simeq 0.29\ \text{steradians} \qquad (17)$$

Although equation 17 is derived in the equatorial plane, it is a reasonable average over the upper part of the shell at L=1.3 where the flux peaks because the line is short and has nearly constant altitude around the equator where $dr/d\theta = 0$.

For Jupiter, on the other hand, the area that is effective in contributing neutrons on shells at large L is the region over which primary cosmic rays of energies comparable to those that hit the Earth in its equatorial region can reach the atmosphere of Jupiter. The region between the δ and δ' cones in this case (again for $\theta \simeq 1/3$ radian) includes a larger portion of the planet over the distant parts of the field line ($\lambda \leq 60°$) where injection goes into pitch angles that mirror significantly above the atmosphere. Two properties of the cosmic rays and their interactions are responsible for these polar regions providing the major CRAND contribution on Jupiter.

1) The integral cosmic ray spectrum falls off rapidly (approximately as $E^{-1.7}$) so that the number of protons of energy (large compared to vertical cutoff) is very small.

2) The number of albedo neutrons in the fixed energy range appropriate to trapping in the portion of the belt under consideration (50 MeV $\leq$ E $\leq$ 1 GeV) per incident primary

is roughly independent of primary energy over the range of primary energies from 10 to 100 GeV. The neutron production interactions are not well known, but this statement applies for a typical intranuclear cascade interaction.

From equation 4, the large jovian vertical cutoff rigidity restricts 15 GeV incident protons approximately to latitudes where

$$\cos^4\lambda \leq 1/210$$

or

$$|\lambda| \leq \lambda_1 = 75°$$

At any point along the field line, one or both polar caps may be in view. Then, the injection solid angle $\Delta\Omega$ at that point is the projection of the total area of these two regions normal to the line of sight divided by the square of the distance r_1 from the field point to the surface. As the field point gets close to the surface, an integration becomes necessary. We restrict consideration to regions where $R = L\cos^2\lambda >> 1$. Then r_1 can be approximated by R which is the distance from the center of Jupiter to the field point.

We approximate the source region of albedo neutrons as a small ellipse when viewed from the injection point. The major axis of this ellipse in all cases subtends an angle of approximately

$$\Delta\psi' = \frac{2\left(R_J\cos\lambda_1\right)}{R}$$

about the injection region. The minor axis is evaluated for two cases:

1) $\lambda < 15°$, where both polar regions are within line of sight, neither completely;

2) $\lambda < 15°$, where essentially all of one polar region is visible.

In case 1), Figure 6 shows that the minor axis of the nearest polar region subtends an angle

$$\Delta\theta' = \sin^{-1}\frac{1}{R} - \chi$$

where

$$\sin\chi = \frac{\sin(\lambda_1 - \lambda)}{R_2} \approx \frac{\sin(\lambda_1 - \lambda)}{R - \cos(\lambda_1 - \lambda)}$$

For the other pole [2)], the equivalent angle is obtained by changing $\lambda_1 - \lambda$ to $\lambda_1 + \lambda$. Hence, the total minor axis is

$$\Delta\theta = 2\sin^{-1}\left(\frac{1}{R}\right) - \sin^{-1}\left(\frac{\sin(\lambda_1 - \lambda)}{R - \cos(\lambda_1 - \lambda)}\right) - \sin^{-1}\left(\frac{\sin(\lambda_1 + \lambda)}{R - \cos(\lambda_1 + \lambda)}\right)$$

$$= \frac{2(1 - \sin\lambda_1\cos\lambda)}{R} + O\left(\frac{1}{R^2}\right)$$

where $R = L\cos^2\lambda$, and O is to be read "the order of."

The total solid angle for $\lambda \geq 15°$ is then

$$\Delta\Omega = \frac{\pi}{4}\,\Delta\psi'\,\Delta\theta'$$

$$= \frac{\pi\cos\lambda_1}{L^2\cos^4\lambda}\left(1 - \sin\lambda_1\cos\lambda\right)$$

At angles above 15°, the minor axis is essentially just the diameter of the circle viewed at an angle of λ to its normal (e.g., for the case L = 18, we found that the angle to the normal was 51° when = 45°). Thus, for $\lambda \geq 15°$

$$\Delta\Omega = \frac{\pi\cos^2\lambda_1}{L^2\cos^3\lambda}$$

The maximum latitude of injection that leads to trapped orbits occurs essentially at the point where the gangent to the field line (i.e., the

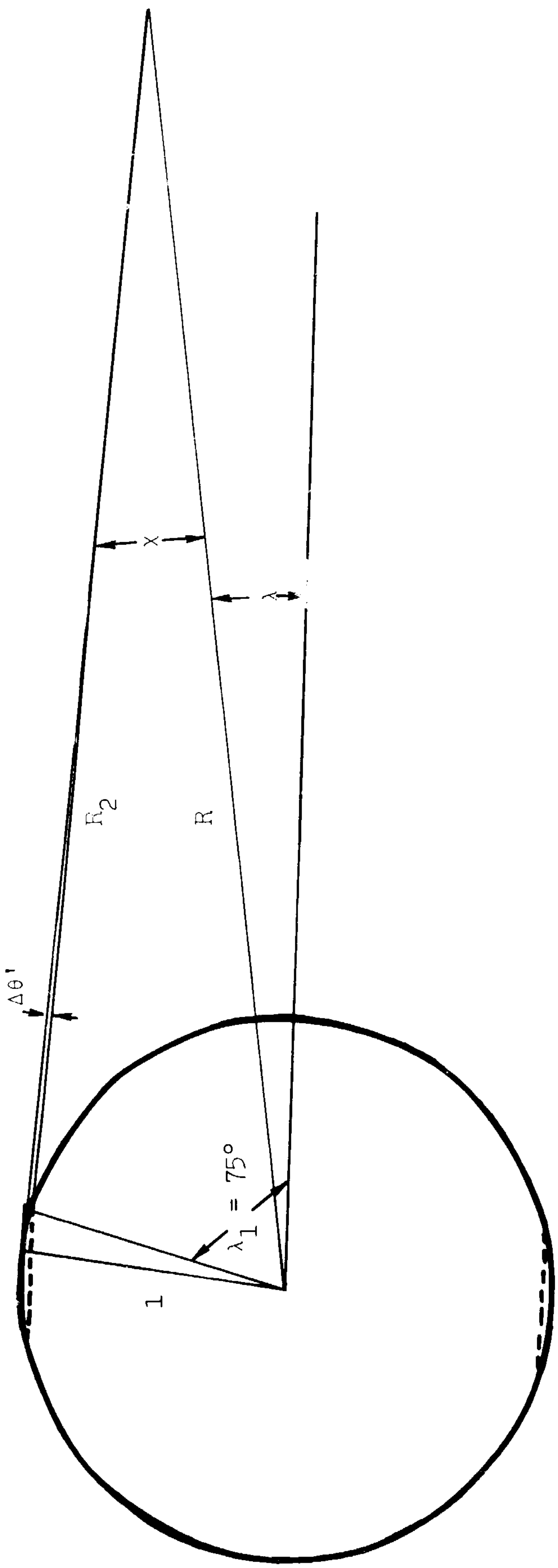


Figure 6. Injection at Low Latitude, Large L

direction of $\vec{B}$ field) is also tangent to the jovian atmosphere. For large L, this latitude λ_M is given by

$$\cos\lambda_M = \left(\frac{2}{L}\right)^{1/3}\left[1 + \frac{1}{8.2^{1/3}L^{2/3}} + O\left(\frac{1}{L}\right)\right]$$

Thus, by equation 16,

$$\overline{\Delta\Omega} = \left(\frac{L}{s}\right)\frac{\pi\cos\lambda_1}{L^2}\int_0^{\pi/12}\frac{\sqrt{1 + 3\sin^2\lambda}}{\cos^3\lambda}\left(1 - \sin\lambda_1\cos\lambda\right)d\lambda$$

$$+ \frac{L}{s}\frac{\pi\cos\lambda_1}{L^2}\int_{\pi/12}^{\lambda_M}\frac{\sqrt{1 + 3\sin^2\lambda}}{\cos^2\lambda}\,d\lambda$$

or

$$\overline{\Delta\Omega} \simeq \frac{0.3234\sqrt{\left(\frac{L}{2}\right)^{2/3} - 1} - 0.1627\cos^{-1}\left(\sqrt[3]{\frac{2}{L}}\right) - 0.03104}{L^2\left(1 - \frac{1}{1.38L}\right)} \qquad (18)$$

At L = 18

$$\overline{\Delta\Omega} = 1.24(10^{-3})\text{ steradians}$$

Equations 17 and 18 provide a relative measure of the injection rates at Jupiter and at L = 1.3 on Earth.

Solar Neutron Decay Injection

An additional source of energetic protons is solar neutron decay (SND). It is important to note that the relative importance of this source at Earth does not significantly affect our estimates of relative source strength. The solar neutron flux at the Earth was estimated by Lingenfelter and Flamm (1965) from the interplanetary proton flux measurements. (Proton diffusion effects which may lower the neutron flux by as much as a factor of

60 (Roelof 1966) were neglected). The resulting solar neutron decay source[1] dominates CRAND for $50 \leq E \leq 200$ MeV in the Earth's inner belt (Claflin and White, 1970).

SND scales to Jupiter differently from CRAND. The L-dependence of SND is slight and is largely due to the planet's shadow. Hence, the ratio of the solar neutron flux at Jupiter's orbit (5.2 AU) to that at earth is simply:

$$j_J/j_e = \frac{1}{(5.2)^2} \exp\left(- \frac{5.2 \times 1.5 \times 10^{13}}{c\tau\sqrt{\gamma^2 - 1}}\right) = \frac{1}{27} \exp\left(- \frac{2.6}{\sqrt{\gamma^2 - 1}}\right) \qquad (19)$$

where τ is the neutron's mean lif[e] $\tau \approx 1010$ sec, and γ is the ratio of total energy to rest energy. Thus, j_J/j_e is the order of 10^{-5}, 10^{-4} and 10^{-3} at 50, 100 and 300 MeV, respectively. The energy dependence of this ratio was not stressed by Carr and Gulkis (1969).

Hence, the trapped proton spectrum at ≈300 MeV at about 18 jovian radii is nearly independent of the relative importance of CRAND and SND in the inner Van Allen Belt.

Loss Mechanisms

The quasiequilibrium flux of trapped protons is given simply as the product of the injection rate and the lifetime. Lifetime in general is a function of energy, L-shell, and mirror latitude, but uncertainties are so great in this area that we estimate flux with one constant value.

The lifetime τ may be limited by any of:

1) Ionization loss due to scattering (chiefly with the electrons) in the background plasma or atmosphere
2) Nuclear scattering with background protons or other nucleons

[1] *It is a minor source if Roelof's result is used.*

3) Hydromagnetic diffusion

4) Plasma instabilities.

At Earth, the first two mechanisms are thought to be primary factors in determining inner-belt CRAND proton lifetimes with a possibility that the third accounts for some of the as yet unresolved disagreement between theory and observation. In the regions of large L on Jupiter, the lifetimes set by *mechanisms* 1) and 2) are quite long. Both scattering-loss lifetimes scale linearly with the background density (the electron density for mechanism 1)). We believe that the plasma density in the Jovian magnetosphere is $\lesssim 100\ cm^{-3}$ (protons or electrons) throughout the region under consideration (lowest altitude of mirroring $\gtrsim 2\ R_J$). We cite several references to support this view, but uncertainties are well summarized by Carr and Gulkis (1969). Warwick (1965) cites upper and lower bounds of 20 and 0.1 cm^{-3} from limits on observed Faraday rotation of the elliptically polarized decametric bursts. Ioannidis and Brice (1970) consider theoretically all the source and loss rates for plasma in the Jovian magnetosphere and derive a maximum density in the magnetosphere of about $10^2\ cm^{-3}$, where the dominant limiting factor at large L is interchange instability. We note that Gledhill (1967) and Piddington (1967) invoked hot, dense plasmapheres to explain the decameter bursts and their correlation with Io. However, Goldreich and Lynden-Bell (1969) provide an alternative model (that seems to explain better the small source region in the ionosphere and the polarization) that requires an average density between Io and Jupiter of only 0.5 cm^{-3}.

The scattering lifetime of a 100 MeV proton in a medium with 100 electrons/cm^3 is $\sim 2(10^4)$ years. This long life may imply that the more uncertain hydromagnetic diffusion or plasma instability processes are the major factors in limiting the lifetime. However, diffusion times for a 100-MeV proton in the convective E field of 3 kV per Jovian radius calculated by Brice and Ioannidis (1970) are extremely long, if the usual assumption of conservation of magnetic moment is made. The lifetime for pitch angle diffusion, on the other hand, is proportional to $(\tau_b/n^2)(B/b)^2$ (Dragt, 1960) where τ_b is the bounce period, n the harmonic number of the resonance, B the main magnetic field and b the amplitude of the magnetic perturbation. Bounce period at large L on Jupiter will be $\sim 10^2$ times the bounce period for the same energy proton in the heart of the Earth's Van Allen belt.

But the nature of the waves is the real question. Plasma instabilities, such as the interchange instability discussed by Ioannidis (1970), may supply the energy to drive such waves, and these waves appear to be required (Carr and Gulkis, 1969) to provide the known fluxes of radiating energetic electrons. Yet, the resonance of these waves with the proton bounce may be poor. A detailed study of the interchange instability at Jupiter along the lines of Chang et al. (1965) may be worthwhile.

Thus, we estimate upper limit CRAND proton fluxes on the basis of a scattering lifetime only. The mean atmospheric density at L = 1.3 has been computed in detail by Cornwall et al. (1965). For mirror points near the equator, the mean electron density is about $10^5 cm^{-3}$. Therefore, with a plasma density of $10^2 cm^{-3}$, the jovian CRAND proton lifetimes would be 10^3 times that at Earth. Figure 7 then shows a flot of the equatorial flux as a function of L on Jupiter as scaled from a peak flux at L - 1.3 on Earth of 3×10^3 protons cm^{-2} sec^{-1} above 100 MeV. Specifically, the function plotted is $\overline{\Delta\Omega} \times 10^7$ where $\overline{\Delta\Omega}$ is given by equation 18. For L > 10, the calculated source may be suspect because of our consistent use of the condition L >> 1.

Conclusions

We have provided quantitative physical arguments for the existence of a high-energy proton belt around Jupiter that extends to distances of the order of 20 jovian radii. The total fluxes are modest compared to others (at this point in time) possible trapped fluxes (e.g., saturated magnetic field models). Nevertheless, a CRAND component should be included in any upper limit model and also in mission design constraints, because sensitive components (when shielded from lower-energy protons) may still be significantly affected by the CRAND protons.

The above calculations probably provide a reasonable upper bound on the high-energy proton flux at fairly large L values ($L \geq 5$). Although more accurate and detailed calculations of the source could be made, these appear satisfactory in order of magnitude. Since the loss mechanism is very uncertain, the chief problem in improving the predicted fluxes is to gain

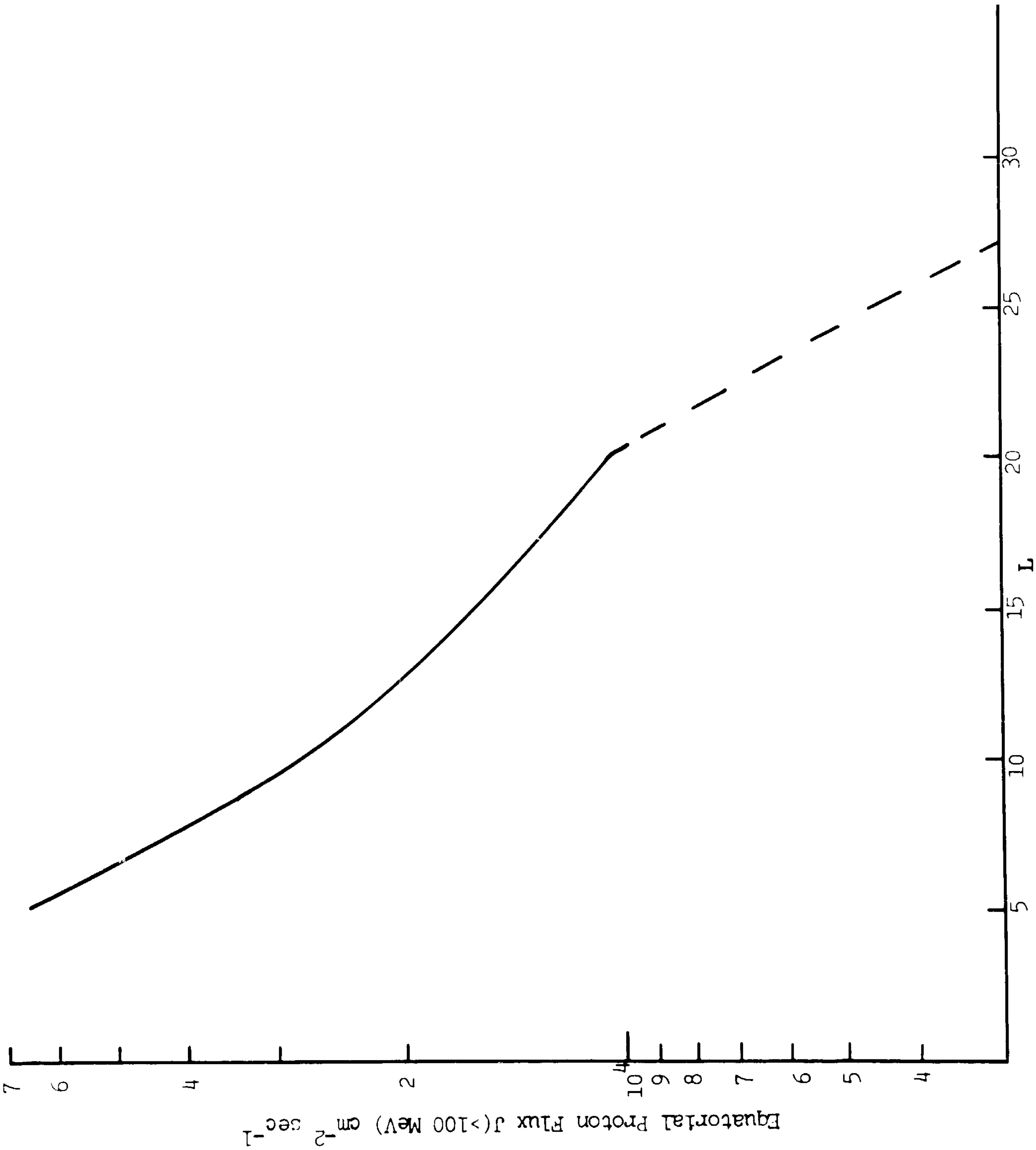


Figure 7. Jovian CRAND Belt Model

understanding of the losses. Further theoretical work here in conjunction with studies of such items as waves in the magnetosphere, plasma instabilities, and the general low energy plasma environment is needed now.

Freden (1969) pointed out in his review that more detailed work is required to understand the Earth's inner belt protons. As noted by Freden, the absolute fluxes near Earth do not agree with calculated values for $E \geq 50$ MeV by factors up to 50, depending on position. One of several possible explanations is an additional source, such as SND. The solar neutron energy spectrum has been calculated by Lingenfelter, et al. (1965[a,b]). It will peak at higher energy at Jupiter because a larger fraction of the lower-energy neutrons decay before reaching Jupiter as given by equation 19. Still, the SND spectrum will fall off more rapidly at high energies than the CRAND spectrum and will exhibit less L-dependence. Thus, comparison of high-energy fluxes (as a function of energy) at Jupiter and Earth may provide a differential analysis of the source spectra. Since the understood diffusion mechanisms do not produce protons at large L in the CRAND and SND energy range from solar wind and storm particles, observation of rather small fluxes of 100 MeV to 1 GeV protons at large L around Jupiter should lead to considerably improved understanding of the CRAND and SND mechanisms in general. From a science viewpoint, this possibility may provide the best rationale for these studies.

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DISCUSSION

DR. TRAINOR: In your model you used a spherical Jupiter, and the source region is very small at the polar caps. As I understand it, Jupiter shows a pronounced flattening. Wouldn't that considerably reduce your source size?

MR. THOMAS: You are right. I could put in oblateness, and assess the answer to that fairly rapidly.

DR. MIHALOV: Did you use a flux at Earth of 100 MeV protons at 3×10^3 cm^{-2} s^{-1} at the peak?

MR. THOMAS: Yes. That is at L=3 at the equator, which I think is slightly beyond the peak.

DR. MIHALOV: At L=1.3, the latest model has a flux about twice that; at the peak it would be 10^4 cm^{-2} sec^{-1}.

MR. THOMAS: At one time, we had considered using 10^4, but I just wanted to get the order of magnitude.

STABLY TRAPPED PROTON LIMITS FOR JUPITER

Charles Kennel*

We originally intented to talk about the Earth's proton belts, but we realized that much of that wasn't too relevant. Therefore, I am going to give a general introduction to pitch-angle diffusion that should apply both in the Earth's magnetosphere and in the Jovian magnetosphere. My purpose is two-fold. We have already had discussions of the fluxes predicted using the concept of stably trapped limits. One purpose is to caution you very greatly against using such ideas for Jupiter, except in limited regions of space. The other one is to act as a shill for my friends, Thorne and Coroniti.

To some extent, we three have been kicking around combining the ideas of radial diffusion and pitch-angle diffusion in the Jovian magnetosphere. Richard (Thorne) will present that. Also, Dr. Neubauer has done a considerable amount of work on the stably trapped limit for Jupiter. We have similar results, but his are in more elegant mathematical form, so I will allow him to present these results.

Typically speaking, when one thinks of what might limit the trapped fluxes in the Earth's magnetosphere, one comes up with the following three types of limiting instabilities:

(1) Interchange or ballooning mode observed during storms, which might limit β to the order of unity.

(2) Electrostatic loss cone modes, ($\omega > \Omega+$) unobservable to date in space, found in laboratory.

(3) Electromagnetic ion cyclotron wave.

The first is an old one--namely, that there is a finite beta interchange or flute-mode instability which redistributes the plasma beta when it gets to be about the order of 1. While we haven't observed this process as a micropulsation event directly during magnetic storms, it appears that this limitation is obeyed because of some magnetic storm data taken by

*University of California, Los Angeles, California 90024

Lou Frank. He observed that the equatorial beta of the plasma during a magnetic storm never exceeds 1 or 2. This seems like a definite limit, empirically, in Earth's ring current; in addition, I think it will be one inside the Jovian magnetosphere, whereas Neil Brice pointed out, one has to put in the corotation.

The interchange is undoubtedly an important mode that needs to be worked on.

The next one that occurs all the time in plasma laboratories and is responsible for the copious loss of protons in laboratory mirror machines is the electrostatic loss cone mode which typically has a frequency near but above the ion cyclotron frequency. The electrostatic loss cone mode is also expected to be important in space. We have seen electrostatic loss cone modes of the type to remove *electrons* in the Earth's magnetosphere. However, to date, no electrostatic wave detector has been constructed which is sensitive down into the few hertz range necessary for detecting proton modes. Therefore, we do not have any information about electrostatic ion loss cone modes in space. Nevertheless, the existence of the electron loss cone modes and the existence of electrostatic modes for ions in the laboratory strongly suggest that these will be important, both in the Earth's magnetosphere and in the Jovian magnetosphere. At the present time, however, we have no idea how intense they are in the Earth's magnetosphere nor what role they play there. About the only thing that we know is that for their generation, they require some sort of wiggle in the distribution function of particles with energy, typically a second bump. It can be a rather small wiggle, and such wiggles have been observed in the ATS 5 satellite; so one rather expects this mode, but I don't know what to do with it other than to point it out to you that it can limit the stably trapped fluxes, as it does in the laboratory.

The third one which has, in fact, been worked upon is the electromagnetic ion cyclotron wave, which is almost in the same frequency range, but below rather than above the ion cyclotron frequency. At very low frequencies, it becomes an Alfven wave, so it is an old friend as far as space physics is concerned. It is just an Alfven wave near the cyclotron frequency. It has a long and honorable history, going back ten years to work by Dungey and others and I need not dwell upon it.

Since this is the only one which has received a lot of attention in the Earth's magnetosphere, we are going to look under the lamp post and talk about the things we know the best. I thought I would give this introduction to indicate that although lecturers always talk about what they know, the things they may not know are probably more important.

Now I would like to turn to the instability theory of the ion cyclotron wave. I am afraid I will just have to summarize how the thing works.

The first point is that this wave can be unstable only if protons can be in cyclotron resonance with the wave. It is a circularly polarized left-hand wave whose electric vector rotates around the magnetic field in the same sense as the proton Larmor motion. When the particle velocity parellel to the magnetic field Doppler shifts the wave frequency to the proton cyclotron frequency in the proton frame, there will be a resonant interaction with the wave. This condition is defined by the equation

$$v_{\parallel} = \frac{\omega - \Omega_+}{K_{\parallel}} \tag{1}$$

relating the particle velocity parallel to the magnetic field, the wave frequency, and the K-vector. Now, we usually talk about the resonant energies because that is what is measured.

One can convert this condition to an expression for the resonant energy by using the dispersion relation

$$\frac{\omega^2}{K^2} = C_A^2(1 - \omega/\Omega_+) \tag{2}$$

for the ion cyclotron wave. Its phase velocity is equal to the Alfven speed squared with a correction which is important near the ion cyclotron frequency; K is determined from this dispersion rate, and substituted for K in Equation 1, and you come up with an expression for the resonant energy in terms of what is measurable--that is, energy and wave frequency as opposed to the velocity and K.

$$1/2m\left(\frac{\omega - \Omega+}{K_{11}}\right)^2 = \frac{B^2}{8\pi N}\left(\frac{\Omega+}{\omega}\right)^2\left(1 - \frac{\omega}{\Omega+}\right)^3 \qquad (3)$$

The resonant energy in parallel motion needed to resonate, to create an instability, and, also, to be scattered by the wave, is related to a characteristic energy, which is just $B^2/8\pi N$. $B^2/8\pi$ is the magnetic energy density, and N is the number of ion pairs per cubic centimeter. Consequently, $B^2/8\pi N$ is the magnetic energy density per ion pair.

I should point out that this is where the Faraday rotation upper limits of the ion pair density play a serious role in whether there is a stably trapped limit for Jupiter or not, and for what energy particles. Also, since the dipole strength could be uncertain by a factor of 2, the resonant energies could go from 100 to 400 MeV in the interesting regions of the Jovian Van Allen belts.

The resonant energy also depends on the ratio of the local cyclotron frequency to the wave frequency.

As we go through the derivation, watch the role of this frequency dependent factor in the resonant energy, because that will define a lower limit to the energy of the particles that can resonate within an unstable wave.

After this, you set up the Vlasov-Maxwell equations, and linearize them through for ion cyclotron waves to find the growth rate.

You pick up a small imaginary part which gives you the growth rate of the instability:

$$\gamma = \Omega_+ \frac{\Omega_+}{\omega} \eta \left[A - \frac{1}{\frac{\Omega_+}{\omega} - 1} \right] \tag{4}$$

The growth rate, gamma, in radians per second, is proportional to the cyclotron frequency, which is the scale frequency for the problem. It is also proportional to the number eta, which is the fractional density of the energetic particles to the background density, and it is proportional to the anisotropy of the particle distribution flux. There will be no instability if there is no anisotropy. If A is zero, in other words, then the wave will be damped.

In summary then, the growth rate is proportional to the cyclotron frequency, the fractional number density of fast particles and the anisotropy of the fast particle distribution.

Now, a necessary but not sufficient condition for instability is that

$$A > \frac{1}{\frac{\Omega_+}{\omega} - 1} \tag{5}$$

Combining this condition with the resonant energy given by Equation 3 leads to a condition on the proton energy given by

$$E_R \geq \frac{B^2}{8\pi N} \frac{1}{A^2(1 + A)} \tag{6}$$

This critical energy is the lowest energy for which the stably trapped limit applies.

Putting the numbers for Jupiter, assuming a 10 gauss magnetic field at the Jovian equator, you find this critical energy

$$E_R > \frac{3 \times 10^6 \text{ Mev}}{L_J^6 \, NA^2(1 + A)} \tag{7}$$

Then, at L equals 2, this critical energy, for N equals 10, at least, is roughly 150 MeV.

Above this critical energy, the particles will arrive at a stably trapped limit, because they will create an instability, they will interact with waves and be precipitated out of the Jovian magnetosphere. Below this critical energy, there exists no stably trapped limit from this instability. Next, we consider only particles above the critical threshold energy and ask what their stability limit might be. In other words, how many of those do you need to create an instability? Then, once the instability is made, you know it removes the particles from the Jovian belts; you would expect, all things being equal, that you would run with a density of energetic particles somewhere near threshold.

We have to face the fact that we are operating with a convective instability in an inhomogeneous medium, so that the real criterion for growth is not simply that there be local amplification, which would be gamma positive, but that there be an integrated *net* growth along the wave path: i.e., the integral along the wave path of the growth rate divided by the group velocity,

$$\Gamma = \int \frac{\gamma}{V_G}\, d\ell \approx \frac{\ell\gamma}{V_G} \tag{8}$$

has to give you a sufficient number of E-foldings in the growth region. If you use the fact that the group velocity is roughly the Alfven speed and approximate the integral simply by estimating the length along the field line, then you can maneuver the growth rate condition around into a condition on the number of resonant particles divided by the background density that you need in order to have some integrated growth along the wave path:

$$\frac{n_R}{N_o} = \frac{\Gamma_o}{\ell}\frac{C_A}{\Omega}\left(\frac{\omega}{\Omega+}\right)\left[A - \frac{1}{\frac{\Omega+}{\omega} - 1}\right]^{-1} \tag{9}$$

Gamma naught should be a number like 10, for instability. In the expression for n_R, you can see that the Alfven speed divided by the length of the growth region, the gyrofrequency, and various frequency dependent factors come in.

If the resonant proton densities exceed this limit, the instability would reduce the resonant proton densities back to these for marginal stability.

Now, let's consider relatively high particle energies above the threshold. From the formula for the resonant energy given in Equation 3,

$$\frac{\omega}{\Omega} \sim \left(\frac{E_R}{\frac{B^2}{8\pi N}} \right)^{-\frac{1}{2}} = \frac{C_A}{V_{\parallel}} \tag{10}$$

In this relationship, a given resonant energy will interact with a certain ratio of wave frequency to cyclotron frequency, roughly at the equatorial plane of the planet. For high-energy particles, the ratio of the wave frequency to the cyclotron frequency is uniquely related to the ratio of the Alfven speed to the parallel particle velocity.

Using the previous expressions, we can get an estimate of the flux

$$J^* = \frac{\Gamma_0}{4A_+} \frac{B_0 c}{4\pi \; eR_J} \frac{1}{L_J^4} \approx \frac{3\times 10^{10}}{L^4} \frac{\Gamma_0}{4A_+} \tag{11}$$

Now, breaking it down into its dimensional pieces, we see the critical flux for instability depends on the required gain, the equatorial magnetic field of Jupiter, the speed of light, charge of the particle, 1 Jovian radius to scale the size of the system, and on the Jupiter L-shell to the minus 4 power.

Surprisingly enough, while the Jupiter magnetic field is up by roughly a factor of 10, relative to Earth, the Jupiter radius is also up by a factor of 10, relative to Earth, so the stably trapped limit for protons is roughly the same as that for the Earth. It is about $3x10^{10}$ protons per square centimeter per second divided by L^4 and then multiplied by a factor which is hard to estimate but is the order of 1. This isn't a very comforting stably trapped limit as far as spacecraft design is concerned, but there it is.

One other point I should mention: because of this L^4 dependence, you can see that near the Jovian magnetopause, where you have 50 to the 4th power in the denominator, the stably trapped flux is very small, and you would expect an instability. We will see that the resonant energies are also very small, so you would definitely expect the region to be unstable far out. I will argue, however, that that is not important for determining the flux levels.

Let's make some assumptions to try to put some perspective on these numbers. If I take Jim Warwick's ion pair number density of 10 per cubic centimeter and if I take the anisotropy of the protons to be roughly that of the electron distribution, I find that the stably trapped limit comes out to be $3x10^9/L^4$, which at L equals 2, is a few times 10^8 per centimeter squared per second.

For these numbers, this stable trapping limit would apply, at L equals 2, to protons above 150 MeV only. Now, at L equals 3, you are down by a third, so it applies to 50 MeV protons (and above) at L equals 3.

The essential point is that while we can be fairly certain about the stably trapped flux limit because it is independent of the density, we do not know enough about the total plasma density to decide which energetic protons it applies to.

As you can see from the numbers, if I were to put the density up or down by a factor of 10, the stably trapped limit could cut in very strongly at low energies and give you an important limit, or it could be totally unimportant.

I would like to make a pitch for good estimates of the density in this context.

There is one more concept which is actually general and does not only apply to this instability.

Even if you have an instability which is scattering particles like crazy in pitch angle and making the distribution isotropic, the particles are not rapidly lost from the system if the mirror ratio, that is, the ratio of magnetic field in the Jovian atmosphere to the equatorial magnetic field strength is very large. The simplest physical picture is simply considering the case where, by some infinitely strong pitch-angle scattering mechanism, a completely isotropic pitch-angle distribution was maintained. You would still, then, get a finite lifetime for the particles: that lifetime would be the bounce time for the particles to get from the equator to the atmosphere times the fraction of the distribution that is in the loss cone at any given time.

For an isotropic distribution, that fraction is just that ratio of the solid angle of the loss cone to that of the hemisphere, π. All pitch-angle scattering losses must give you a larger lifetime.

For a dipole, the minimum lifetime is

$$T_{MIN} = 2T_B L^3 \tag{12}$$

For Jupiter, it is

$$T_{MIN} = 400L^4/\sqrt{\hat{E}(keV)} \tag{13}$$

Consider 1-keV particles at L equals 50. The minimum lifetime is 100 years for that particle to be pitch-angle scattered into the atmosphere.

Therefore, you could go ahead with your radial diffusion solutions, provided they had scale times less than 100 years, without including precipitation losses. Were there any turbulent scattering, the pitch-angle distribution would be maintained isotropic during the radial diffusion, but losses would be negligible. It would be a first invariant violating radial diffusion.

Particles could radially diffuse inward without significant particle loss only until the minimum lifetime becomes comparable with the scale time for radial diffusion. For a radial diffusion solution, pick a typical particle to start at kilovolt at the magnetopause. This energy goes up as 1 over L cubed. Then if you plug that into the minimum lifetime, you find, following that characteristic energy in with L, the minimum lifetime scales like $L^{11/2}$.

At L equals 10, that gives about a four-day lifetime. Therefore, it is only in the near regions of the Jovian magnetosphere, roughly within L equals 10, that you expect the particles to be reduced to the stably trapped limit on the dynamical time scales.

As you get closer in, the critical energy for the stably trapped limit to apply moves to higher and higher energies, and the stable trapping limit becomes less and less important. So there is a narrow region between L = 5 and L = 10 in which it can act as a choke or a throttle for the system. Richard (Thorne) will discuss the effects of this in greater detail. I think the most important thing to point out is that one would very much like to get total density measurements from any probe that goes to Jupiter--plasmasphere density measurements--because if these arguments are correct, they will tell you whether or not you can have a stably trapped limit for protons of interesting energies.

The other argument is, of course, you want to measure the wave fluctuations around the cyclotron frequency, because even if you don't have the density, when you can see the fluctuation of cyclotron waves, you know protons are being scattered.

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DISCUSSION

DR: BRICE: I believe a pretty good estimate of the densities is given in the article, "The Magnetospheres of Jupiter and Earth," Vol. 13, No. 2, 1970.

DR. KENNEL: With all due respect to a fellow theorist, I was also calling for an experimental determination.

DR. BRICE: Charley, what I did was to take the plasma distribution that I have and calculate from that roughly--well, calculate the critical energy and then convert that into a first invariant using the magnetic field strength and then compare that with the first invariant of the particles in the solar wind to see if the particles were diffused in from the solar wind; conserving the first invariant, would the critical energy ever get below the particle energy?

I fairly convinced myself that it almost has to. Someplace in the magnetosphere, the critical energy will get substantially less than the particle energy, so that somewhere in the magnetosphere, probably about L equals 7 or 8, the stable limit will apply.

DR. KENNEL: Yes, we have reached that conclusion.

DR. BRICE: But when you do that and you put in the fluxes and you integrate to get, say, a number density and then put in the energy of the particles that you get from conserving μ, then you find out that you get a limiting β for this mechanism, which turns out to be about 0.1.

DR. KENNEL: That is the β that you get from this mechanism on the Earth. It should be pointed out that with the Earth, you consistently violate that limit with ring current particles below the critical energy.

It is what the ring current is all about. If the magnetic storms obeyed this stably trapped limit, that is, for all protons, you would only get a 20 or 30 gamma depression in the main phase, but you get much more than that. It is because all of the ring current protons are below the critical energy.

DR. BRICE: For Jupiter, they should be above it.

DR. KENNEL: Well, that is from these numbers, I find it--at 150 MeV.

DR. BRICE: My density goes up to 100 per cc at an L of 7.

DR KENNEL: Okay. If the density is 100, instead of 10--then I think the stably trapped limit does cut in very strongly. Ten seems to be right on the borderline of where it will be applicable. If it is much less than 10, you can rule it out for the particles radial diffusion produces.

DR. WARWICK: Just where you don't have data.

DR. BEARD: If you conserve the adiabatic invariant and you assume particles of 400 electron volts, or so, in the magnetosheath, they wouldn't have an energy of 150 MeV at L equals 2. They would have an energy at least an order of magnitude less than that.

DR. KENNEL: That is the point. These critical energies are rather high near L=2.

DR. BRICE: This critical energy goes as L to the 6th, and the energy to the particles goes like L 3rd, so if you put in 100 per cc at L equals 2, it wouldn't do anything for you. The whole point is, you have to combine the number density and where it is. If you put in the 100 per cc at L equals 7, then this limit is applicable. But I still maintain that it is not a very useful one, because it gives you a beta of 0.1.

DR. LIEMOHN: I went through a little bit of arithmetic while you were finishing, and at L equals 10 where Neil has a peak density of 100 particles, you reduce the threshold energy by a factor of 10 because you are talking about the additional cold plasma. Also, because you are further out, that resonant energy has been reduced now by the L^6 and you are down by a factor of 4, so you are talking about 1 to 10 keV. It is a very significant effect there.

DR. KENNEL: But near in, in the synchrotron belts, it is hard to see. It is a bit dicey as to whether it is important in the synchrotron belt.

DR. LIEMOHN: It probably isn't important, but you have effected the total flow in. All it depends on is the loss mechanism.

DR. KENNEL: That we will talk about.

DR. HAFFNER: I would like to make a comment. You have calculated an upper limit based on this pitch angle and an anisotropy instability associated therewith, but if all these particles were emitting synchrotron radiation with any sort of reasonable spectrum and no attenuation mechanisms, we would get appreciably stronger signal strength for the decimetric noise at the Earth than observed. What I am saying is, I don't think the particles get up to this instability limit, at least in any time.

DR. BRICE: This is the electrons. Let's be careful about the protons.

DR. KENNEL: We are trying to guess about the protons. The point is that using a stably trapped limit has two restrictions on it. It applies only to energies above the critical energies, which you can calculate if you knew the density. Also, you must arrange it so that the minimum lifetime is less than either the spatial diffusion or transport times. In that case, then, you would expect the fluxes actually to be precipitated out and reduced to the stably trapped limit before anything else happened. Those are the two conditions on which these ideas work.

As I pointed out, beyond L equals 10, the minimum lifetime is very long. Far in, critical energies are very high. It is not clear that the stably trapped limit applies at the maximum at the synchrotron belts. In between, it could serve to reduce the fluxes, and act as a choke for injection into the inner region.

DR. LIEMOHN: I would like to ask one other question. At the Earth, this resonant lower limit is presumably what? One keV, or so--depending on where you are, of course?

DR. KENNEL: It ranges all over. Richard Thorne and Ferd Coroniti and Mike Cornwall have written a paper on precisely that. It ranges from a few hundred volts just inside the plasmapause to tens of kilovolts just outside.

DR. LIEMOHN: The point I am coming to is that even though you don't have this stably trapped limit, if you will, from this mechanism, the number of particles that are down at those energies decrease rather appreciably in the magnetosphere, I think, and it seems to peak up. If my recollection of the particle data is correct, it peaks up between 10 and 100 keV, and it starts to drop off.

DR. KENNEL: Yes. Where $B^2/8\pi N$ is the order of a few tens of kilovolts--comparable with a few tens of kilovolt particles observed in the ring current--then you have a ring current.

DR. BRICE: There are two factors, Harold. One is what is the stable trapping limit. It says, essentially, that above that, none of the fluxes can be very large, but if the particles are being generated by electrostatic instabilities associated with sub-storms or if they are coming in from the solar wind, then you have some kind of first-order,first-invariant conservation; then you can't get those very low energies very close in because in order for the particles to diffuse in, they have to energize.

DR. LIEMOHN: They are repeating processes, but if there are other sources for particles, they don't materialize, or this particular process--there must be some repeating process that is much more firm.

DR. KENNEL: If you are considering energies below the critical energy, this particular process simply does not work.

DR. LIEMOHN: That is the point I am trying to make.

DR. KENNEL: The point I made is when this does not work, it appears that the Earth's ring current goes to a higher beta--maybe the order of 1--and is limited by something else--perhaps interchange instabilities, as has been suggested. There is, during magnetic storms, a beta 1 limitation. Those fluxes far exceed what you compute for the stably trapped limit. The reason they exceed it is because the energy of the particles in the ring current is below what you need--below this critical energy.

DR. BRICE: However, if we add a small amount of plasma and bring the characteristic energy down, then you get rid of the ring current.

DR. KENNEL: That's right. The really crucial point is to know the density and its profile.

From that, we could--coupled with the radial diffusion solutions--be able to tell where particles are lost and at what energies.

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A SELF-CONSISTENT MODEL FOR JUPITER'S RADIATION BELTS

Richard M. Thorne and Ferdinand V. Coroniti*

The first thing I must stress is that Ferd Coroniti and I have only been thinking about the Jupiter problem for a couple of weeks; so anything which I will present is going to be rather qualitative. I wouldn't like to argue any closer than the nearest order of magnitude.

The point of view we have adopted is that the solar wind can act as a sufficient source for the radiation belts of Jupiter, using radial diffusion as the process for getting the solar wind fluxes into the inner regions of Jupiter's radiation belts. We shall attempt to combine the processes of a radial diffusion source with pitch-angle diffusion losses to try and estimate an upper limit to the fluxes of protons and electrons that might be expected in Jupiter's radiation belts. Towards the end of my presentation, I will argue that the most probable fluxes to be found near Jupiter, whether we like it or not, are going to lie reasonably close to this upper limit.

Charlie mentioned in his talk that there are essentially two factors which are important for calculating particle losses, due to resonant interactions with electromagnetic waves. First, there is a lower limit to the particle energy at which pitch-angle diffusion can occur. Secondly, an anisotropic distribution of the particles in pitch angle is required in order for the instability to produce wave growth. Now, such an anisotropy is, of course, expected, because we have a loss cone distribution of the particles. Particles are being continually lost along the direction of the magnetic field, and they are also being preferentially injected by the radial diffusion process, such that the fluxes are larger perpendicular to the field than in any other direction. Without pitch-angle scattering, the anisotropy should increase as one moves in towards the inner regions of the radiation belts. This results because the perpendicular energy will scale like the field ($E_\perp$ L^{-3}), whereas the

*University of California, Los Angeles, California 90024

parallel energies will scale as $E_{||} \sim L^{-2}$. Thus for a rough estimate of the particle anisotropy, (in the event that losses are negligible) one may assume that it should scale like L^{-1}. Starting with an isotropic distribution near the solar wind boundary would yield a pitch angle anisotropy of about 5 at $L = 10$.

Now, referring to Figure 1, we will make some quantitative estimates. The horizontal axis gives the radial L values, up to L = 16. This has been given a logarithmic scale in order to accommodate a large region of the radiation belts. In Figure 1, I have plotted various energies that are characteristic of Jupiter's radiation belts. Notice that the scale ranges from 10 KeV to 100 BeV. Charlie mentioned that $B^2/8\pi N$ was going to be a typical scaling energy which would decide whether or not particle fluxes could be made unstable. If the particle energies lie well below this, one cannot reasonably expect instability to occur. On the other hand, for energies above $B^2/8\pi N$, the unstable resonant cyclotron interaction should occur giving rise to pitch-angle scattering loss which reduces the fluxes of particles to the stably trapped flux limits, which Charlie presented. To construct the $B^2/8\pi N$ profile in Figure 1, we have adopted Neil Brice's cold density profile and taken a centered dipole magnetic field with 10 gauss at the Jovian surface.

The next important question to ask is what sort of energies would be of interest for Jupiter's radiation belts. To answer this, I have taken two characteristic magnetic moments; 100 MeV per gauss, which corresponds to a typical solar wind proton, and 10 MeV per gauss, which may be more realistic for particles which have suffered considerable violation of μ in moving from the solar wind into the magnetosphere. For Jupiter, values of μ probably lie between these two extremes.

But despite this uncertainty in μ, one can readily see that the $B^2/8\pi N$ curve conveniently devides the radiation belts into two distinct regions. In the outer zone, typical energies exceed $B^2/8\pi N$ and thus, provided the pitch-angle anisotropy is greater than or comparable to 1, one would expect particles to be unstable in this region. Closer into the planet, the radiation belt energies lie well below $B^2/8\pi N$ and one thus expects relative stability to

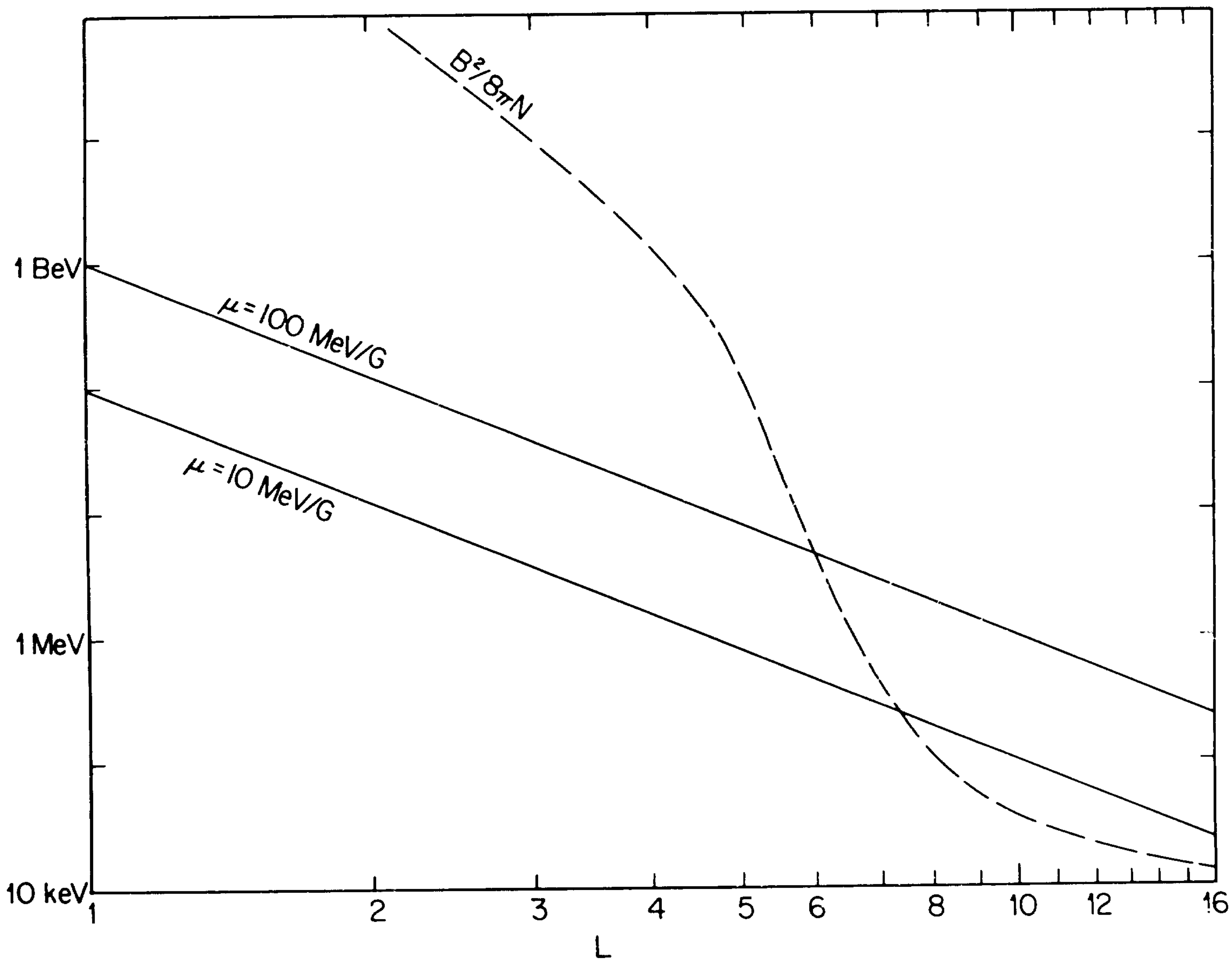

Figure 1. Characteristic energies in the Jovian Radiation Belts. $B^2/8\pi N$ represents the minimum energy for electromagnetic instability.

electromagnetic turbulence. As Neil has already pointed out in his talk, the crossover point occurs in the region between 6 to 8 Jovian radii depending on the radiation belt energy.

Another way to look at the problem is to ask what the pitch-angle anistropy must be to ensure instability of the expected dominant radiation belt particles. In the outer zone (L 6 or 8) anisotropies of order unity suffice whereas the inner zone requires enormous and certainly unattainable anisotropies. We should thus have a stable inner zone in which any injected flux can remain trapped for long periods of time, and a highly unstable outer zone which should be subject to reasonable rapid temporal fluctuations.

Let us first consider the outer zone. Here, pitch-angle diffusion should be rather effective, and this will keep the pitch-angle anisotropy to reasonably low values. One can therefore not expect the anisotropy to increase rapidly as particles diffuse in.For the present discussion,I will assume that the anisotropy is maintained close to or less than unity in outer regions of the radiation belts. This has the effect of limiting the anisotropy permitted in the inner zone. For example, if one starts with an isotropic distribution near the critical boundary for instability ($L \sim 6$ to 8), then one could never expect anisotropies of more than, say, 3 or 4 in the region near $L = 2$. These values, however, are close to the anistropies that are needed to explain the synchrotron emissions. This also ensures that it is going to be almost impossible for the particles to become unstable in the inner zone: the energies are just too small.

Well,let's go ahead to Figure 2,and look at the lifetimes one expects for the unstable particles in the outer zone.Figure 3 shows that the fluxes one typically expects for particles diffusing in from the solar wind are likely to exceed the stably trapped limits that Kennel presented.Consequently,one must expec the particles to be subject to pitch-angle scattering close to the strong diffusion limit. This also means that their lifetimes are probably reasonably close to the minimum lifetimes τ_{min} which he presented. I have roughly sketched what these should be for protons and electrons in the Jovian radiation belts.

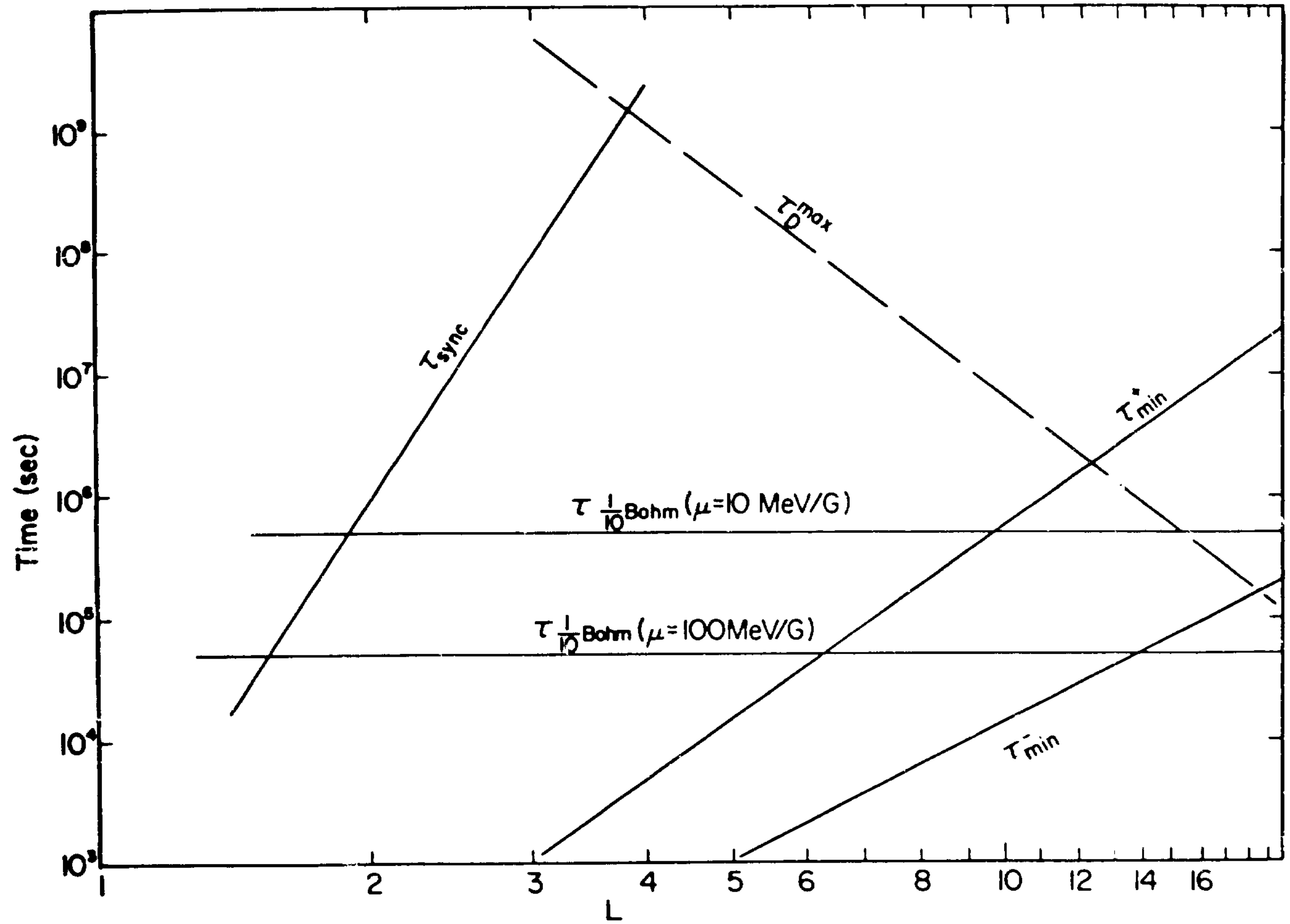

Figure 2. Characteristic time scales for proton τ^{+}_{min} and electron τ^{-}_{min} loss and radial diffusion injection τ^{max}_{D}. Electron synchrotron loss times are plotted as τ_{sync} and $\tau_{1/10\ Bohm}$ represents the maximal rate of inward radial diffusion.

The important fact to notice is that the minimum lifetime for protons τ^{+}_{min} drops off like $L^{11/2}$. For electrons, however, the minimum lifetime drops off like L^4 because these particles are essentially relativistic throughout most of the radiation belts, and the minimum lifetime depends on the velocity of the particles under consideration.

In order to estimate how far particles would penetrate before they are subject to severe losses, one has to make some assumptions for the source time scale. For the purpose of the present discussion, I will assume that there is no CRAND[1] source or other local source for the particles. We are just going to assume that the solar wind provides the source by radial diffusion. The diffusion coefficient that I have adopted to make an estimate of where losses start to become important is based on fluctuating electric fields and thus scales as L^6. The magnitude of electric field diffusion has been taken at the minimal level to get past Io without severe losses. To do this, I have used Dr. Mead's estimate that the loss time is roughly two days at Io. Notice that this is not the 10-hour corotation time, but rather two days, because the particles are bouncing across the equator as they diffuse in. To compare this with pitch-angle losses, I have plotted the effective time scales to diffuse one Jovian radius at this minimal rate to bypass Io, and I have scaled $\tau_D^{max} \sim L^{-6}$ (which is appropriate for electric field diffusion).

Now, from the electric diffusion coefficient $D_E \sim (c^2/2B^2)P(\omega_D)$, one can estimate that a fluctuating power spectral density of 3,000 mV per m^2 per Hz is required.

For comparison, Moser has made measurements of fluctuating electric fields in the Earth's magnetosphere. His measured electric field power at the 10-hour time period of interest in the Jovian radiation belts are a factor of 100 higher than the above estimate. So even if we say that the fluctuating electric fields on Jupiter are scaled down by a factor of 100, it seems as though this would still be adequate to diffuse the particles past the orbit of Io. This corresponds, by the way, to an electric field of roughly one-third

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[1] *cosmic ray albedo neutron decay*

mV per meter, if one adopts a correlation time of 10 hours to make the estimate. Now, such an electric field would require that the entire potential drop provided by the quiet solar wind across Jupiter's magnetosphere be impressed throughout the radiation belts. If you allow for solar wind disturbances, the electric field across Jupiter could well be a factor of 10 higher than this. Thus, diffusion at the required rate could take place under disturbed solar wind conditions if one tenth of the electric field in the solar wind is impressed across the magnetosphere of Jupiter. I don't think these estimates are terribly liberal.

The major point to be gained from these estimates is that protons can readily diffuse into the region defined by the intersection of the source and loss time scales--here at $L \approx 12$. At large L values, the diffusion is much faster, and as soon as one reaches this boundary, losses start to dominate. One should thus expect the proton flux to drop rapidly to the stably trapped flux levels within this location. In the outer regions of the radiation belts, the source is sufficiently rapid to allow fluxes to exceed the stably trapped flux levels.

For electrons, the boundary lies further out because the minimum lifetimes are shorter. For the same radial diffusion coefficient, the boundary occurs at 18 Jovian radii. Again, within this location, the fluxes of electrons should be reduced to the stably trapped flux levels.

One can, of course, take any other diffusion coefficient and change these numbers appropriately. Another diffusion coefficient which we stuck on for fun--I am sure Neil will have something to say about this--is due to Bohm diffusion. The justification for adopting such a rapid diffusion is that in any plasma device, diffusion always proceeds much faster than any of the known mechanisms which have been worked out theoretically. Typically, diffusion occurs at one-tenth of the maximal rate, which itself is defined by the transport of particles over a Larmor radius within a Larmor period. I have plotted Bohm diffusion times for μ = 10 MeV per gauss and 100 MeV per gauss, assuming that it proceeds at one-tenth of the maximum rate. This should be an absolute upper limit to the rate of inward diffusion. The two time scales plotted (see Figure 2) are independent of L, which is rather nice. It means that if this process works, one does not have the problem of the diffusion rate scaling like some high power of L. This doesn't make very much difference in the outer regions of the belts, but it is going to make a tremendous difference near the heart of the belts at $L \approx 2$.

Finally, I have added the synchrotron energy loss time scale to emphasize the fact that if one had electric field diffusion, one would expect to see a very sharp boundary of high electrons due to the synchrotron losses. For the chosen electric field diffusion coefficient, the electrons should rapidly begin losing energy at about 4 Jovian radii. To let the high energy electrons penetrate any further than that, one would have to take very much larger diffusion rates. In fact, to get them into where the peak of the synchrotron radiation is seen, one would need something comparable to Bohm diffusion. The Bohm diffusion intersection would occur at about 1-1/2 to 2 Jovian radii. Of course, the electron energy loss will increase the synchrotron lifetime and thus permit deeper penetration.

Well, with these qualitative time scales in mind, let's go on to Figure 3, and make estimates for the fluxes of particles. Here, I plotted on the critical stably trapped flux limits multiplied by the particle anisotropy, $J^{*}A$. This roughly agrees with the numbers that Kennel presented.

The next question to ask is what fluxes can be expected from the solar wind radial diffusion source. For an external source such as the solar wind, the differential flux can at best increase like L^{-3}. From the diffusion equation, it turns out that if the flux increases any faster than that, diffusion will not act as a source; rather it will act as a sink! As long as μ is approximately conserved, the direction in which diffusion operates is defined by the gradient of the perpendicular differential flux times L^3. If one wishes to increase the flux any faster than that, radial diffusion must be excluded as the source. One would require some internal source. Thus one can plot an upper limit to the solar wind compressed fluxes, here shown for direct

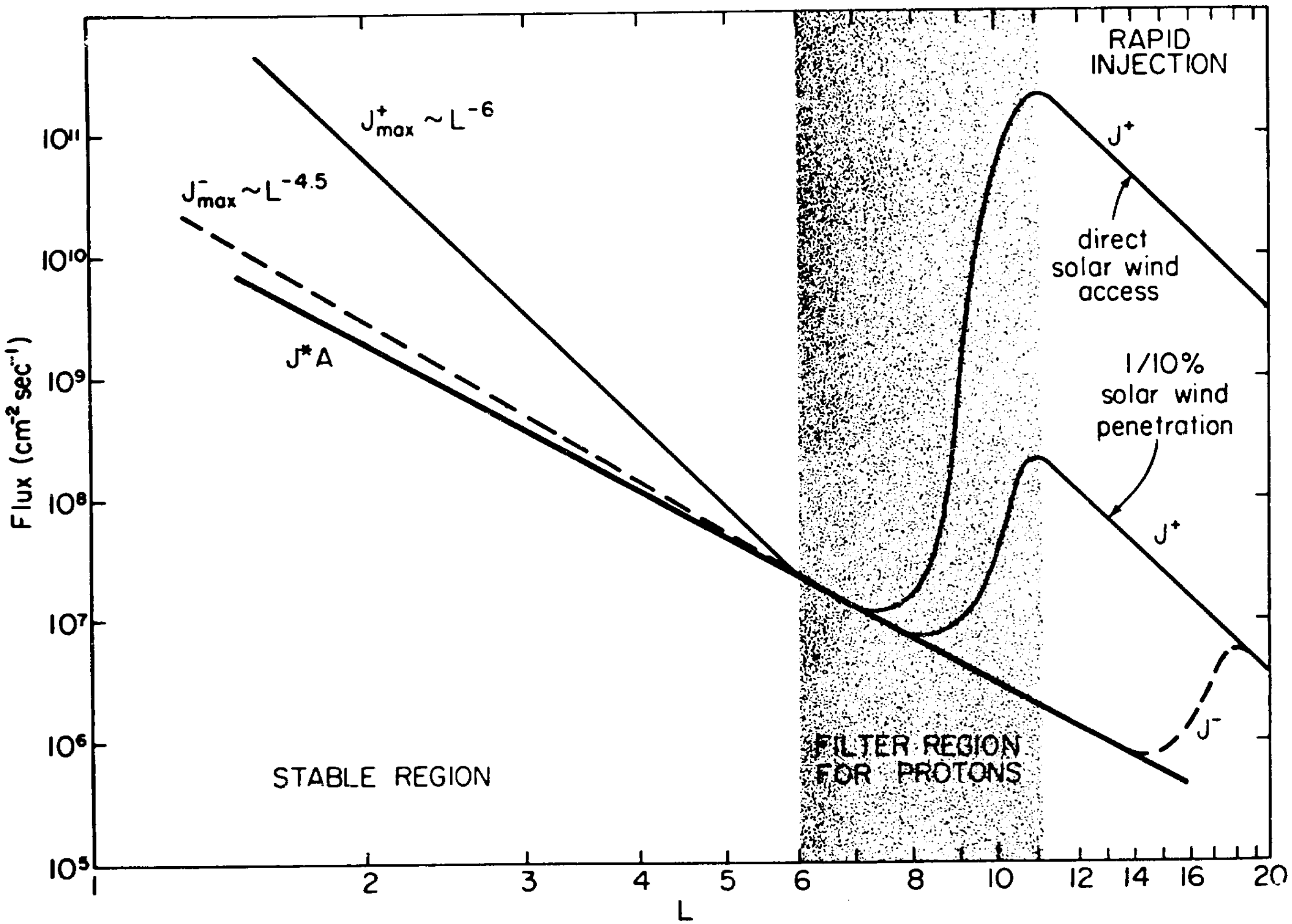

Figure 3. Theoretical integral flux profiles for characteristic Jovian radiation belt particles. Protons are limited to the stably trapped flux levels by electromagnetic instability in the region between 6 and 12 R_J.

access and for a one-tenth percent solar wind penetration. The upper limit to the integral proton and electron fluxes in the outer zone scale like L^{-6} throughout the outer zone, assuming μ is approximately conserved.* The important thing is that these fluxes are above the stably trapped flux levels in the outer regions of the belts; we also know that the instability will work because the energies of the particles are above the critical value required.

DISCUSSION

DR. BRICE: What density did you use to get that critical value?

DR. THORNE: Your densities. I remember your densities were essentially a tenth--very close to the planet. They reached 1 around about 5 and peaked at 100 particles at L = 10, or so.

DR. BRICE: I tried various densities and anistropies. I couldn't realistically get that curve to be above the others all the way in. I think that it is a pretty strong assumption that it does drop off.

DR. THORNE: I think we have two bracketed regions--one of stability and one of instability. In Figure 3, the point I wish to make is that if you allow one-tenth of one percent of the solar wind to penetrate across the boundary, the maximum rate at which the flux could increase by radial diffusion would follow the lower line.It would then eventually reach the point at which the injection time scale by diffusion balanced the precipitation time scale due to strong precipitational losses. The fluxes should then drop within a scaling distance of 1 Jovian radii or so, to the stably trapped flux levels. They should then remain at this level into the innermost boundary, defined by the location at which the particles become stable to cyclotron instability. From this point on in, one can again scale the flux at the maximum rate allowed by radial diffusion in order to obtain upper limit curves. For protons which are nonrelativistic, the *integral* flux varies at L^{-6}, whereas relativistic electrons scale like $L^{-4.5}$ throughout the inner zone.

**Figure 3 has been modified from that presented at the workshop. Initially, we had eroneously been using differential flux, but integral fluxes are of more direct interest for radiation hazards.*

One major conclusion is that the regional rapid cyclotron pitch-angle scattering will act as a filter on any particles which are diffusing in from the solar wind. It doesn't matter how much of the solar wind diffuses in--even if all of it diffused in--you would still reduce the fluxes to the stably trapped level throughout this region. For electrons, it is even better because they become subject to strong losses further out than the protons, because their lifetimes are shorter.

A second point I would like to stress is even if one has an impulsive injection of particles, say, following magnetic disturbances on the sun, the fluxes which one would find in the inner zone probably wouldn't show any significant time variation because of this filtering effect throughout the region of instability where the fluxes are always reduced to the stably trapped flux level.

Now, the other interesting point is if you scale the stably trapped flux levels from this innermost boundary of instability--scale it like $L^{-4.5}$ which is the maximum rate you can allow the electron flux to increase--the fluxes in the heart of the electron belts would come to about 10^9. Of course, by that point the electrons are subject to strong synchrotron losses, which will limit the fluxes of high energy electrons. The limiting fluxes in the loss region would apply to both electrons and protons, because the stably trapped flux levels are independent of species.

DR. BRICE: Except the electrons are highly relativistic in here, so you have got to use a relativistic pitch-angle diffusion.

DR. THORNE: Let me deal with the electrons first, and then we will go back to protons, because I think, as Neil Brice pointed out yesterday, the electrons give you a rather nice constraint on what we would expect for the protons if this sort of physics is operating.

If one assumes that the fluxes in the heart of the synchrotron region are reduced by a factor of 10 to 100 from these limiting values (which is probably reasonable because the synchrotron losses are severe) the corresponding number densities come pretty close to the values one would need in order to understand the synchrotron emissions; that is, number densities between 10^{-2} and 10^{-3}. Now, I think Dr. Luthey's densities are somewhat lower than that, but maybe he could comment on that after the talk. But these seem to agree with the measurements which Davis and Chang presented.

DR. DAVIS: Will you explain how the synchrotron losses make the fluxes lower? I can see how they make the energies of the particles lower, but I don't see how they reduce the flux. It is all relativistic, anyway.

DR. THORNE: That's a good point. The total number of particles will remain the same but those contributing to the synchrotron emission will be lower.

DR. DAVIS: Why are you confident that the density increases as you go in just at this $L^{-4.5}$ level?

DR. THORNE: This is the maximal rate which it could increase. It couldn't increase any faster. It could be flat, or it could decrease, but I am just trying to put an upper limit on the fluxes. I do not think that these could be any more than that.

DR. DAVIS: If you have anything which is removing particles so that you have to get a very definite flux in by your diffusion mechanism, then you have got to have a smaller number of particles inside.

DR. SCARF: In connection with your statement about this being an upper limit, is it not true that you are discarding the electrostatic instabilities in all of these calculations?

DR. THORNE: Electrostatic instabilities may put a different upper limit on the stably trapped flux J^*.The limiting fluxes presented here are purely on the basis that ion-cyclotron losses are going to provide the dominant loss process.

DR. SCARF: Suppose you assume that the other instability were of equal importance? What sort of changes would come in this picture?

DR. KENNEL: I don't think in a qualitative sense it would make much difference, at least for the region of stability. Once again, it depends on the density. The theoretical studies of those instabilities all indicate that their growth rate depends on the ratio of the plasma frequency to the cyclotron frequency. If that ratio is larger, it is easier to make an instability. On the other hand, if the density is very low, it takes a gross distortion of the distribution function to make an instability in the outer region. Where the background density is high therefore, you have to talk about the competition between electrostatic and electromagnetic instabilities.

In the ring current, you see no limitation until the beta gets to be on the order of one. What that limitation is due to, I haven't the slightest idea.

DR. BRICE: We appear to see substantial precipitation of electrons due to electrostatic waves.

DR. SCARF: If we take a look at the electron situation as an analogy, or use that as any guide during substorms, the electrostatic waves could be more important or at least as important in precipitating the electrons than the electromagnetic waves, although both are effective.

DR. BRICE: They don't appear to wipe out the protons as badly as they do the electrons.

DR. KENNEL: That is a minimum lifetime argument. The minimum lifetime of electrons is shorter than the substorm; the minimum lifetime of protons is longer than the substorm. Even if the protons are isotropically scattered in the substorm, you wouldn't lose them until it was all over, and that is what is observed.

DR. SCARF: I have just one more question concerning your diffusion estimate of Bohm diffusion. It doesn't seem really fair to me to put Bohm diffusion on everywhere. But it might be reasonable to assume that Bohm diffusion does operate in certain regions.

DR. THORNE: We are not using Bohm diffusion everywhere. What we are saying is that in order to understand how the electrons could possibly get into the region where synchrotron radiation is seen most intensive, you need something pretty close to the Bohm mechanism.

DR. KENNEL: It could very well be Neil Brice's mechanism.

DR. BEARD: I have two comments. First, the first adiabatic invariant μ that you use is 100 MeV per gauss in the solar wind, and you suggested that might be reduced to 10 MeV per gauss.

DR. THORNE: We don't really understand what the boundary of Jupiter will look like, as Neil pointed out yesterday. It could be very different from the Earth.

DR. BEARD: The point that I was going to raise was that in the Earth, the magnetic field is not very heavily loaded in the magnetosphere. When you do have a sudden increase in the magnetic field, then across the boundary, you would expect the μ to lower quite a bit--perhaps by more than a tenth near the sub-solar point. Regarding Jupiter, I found Neil's talk very persuasive on the point that plasma-loading of Jupiter's magnetosphere could be very great, and too, that the magnetic field would not decrease as you crossed the boundary. Therefore, μ would remain about the same.

DR. THORNE: Well, these calculations for the stably trapped flux are independent of energy, at least for the protons. Of course, for the electrons, as Neil Brice pointed out, must be revised to include relativistic corrections.

That has not been done.

DR. BRICE: I think that it is very important to do this, because at the present time, I would say it looks as if the fluxes for the electrons that you arrive at by this process are larger than the ones in the synchrotron region.

DR. KENNEL: That is solved in the paper by Flesco. It indicates that the relativistic limit of the stably trapped flux is somewhat lower.

DR. BRICE: I think it has to be, because the velocities bunch up, so the resonant fluxes are going to be larger. I conclude they would be lowered, too, but it is critical whether it is a factor of 3 or a factor of 100.

DR. BEARD: The other comment that I was going to make was that you mentioned that the anisotropy for the electrons probably would go as $\frac{1}{L}$ from some intermediate distance.

DR. THORNE: Only from the stable point, inwards.

DR. BEARD: And that it would yield an anisotropy of maybe a three? But the synchrotron emission would increase that anisotropy because the particles that mirror low, radiate away their energy very quickly, compared to the particles which have large pitch angles.

DR. THORNE: I would argue another way, and that is, synchrotron radiation is taking energy from the perpendicular motion of the particle.

DR. BEARD: It is taking energy from the perpendicular motion. As they penetrate, it changes the pitch angle, but not very much. However, particles with low pitch-angles are quickly lost.

DR. KENNEL: That is true, though I think the basic point is that since the particles loss rate varies as L^9 in one direction and the diffusion rate varies as L^{-6} goes in the other direction, there is at least an L^{15} dependence for any diffusion coefficient. Thus, the pitch-angle distribution controlled by synchrotron emission will be found only on the inner edge, where the belts are dropping off. Beyond the maximum it should be determined by radial diffusion, because it is a faster process.

DR. BRICE: It is the ionospheric turbulence that is driving it essentially at L^{-6}. It is going to get better and better as you come in. It likely would be L^{+2}. The plasma interchange that I talked about yesterday is L^{-2}.

DR. KENNEL: I still don't see it exceeding L^9.

MR. BECK: Isn't it the case that this process is really setting an absolute upper limit?

DR. THORNE: An upper limit can be set at least for these protons, because the protons are nonrelativistic. Our reasoning is that the results which are known to apply for the Earth's radiation flux should apply here, too. For the electrons, it is a different story because of the relativistic corrections. A major factor is that the loss time scale for the protons are going to be enormous. I don't know if anyone could make estimates, but it is probably millions of years more. We know that the electrons are injected with time scales on the order of a year in order to beat the synchrotron losses. This must be so unless you have an additional source for synchrotron electrons close in.

Unfortunately, on the basis of electromagnetic losses alone, I think it is an upper limit which probably has to be approached, because any reasonable diffusion time one takes--provided that the diffusion times of electrons and protons are comparable, can always beat losses of protons. Although the injection time scales can be much shorter than the losses, one can still never beat this L^{-6} flux profile for protons.

DR. BRICE: The question is, how much do you bring it down because of a loss rate?

DR. THORNE: I think it is a question of relative time scales. If the time scales for diffusion is a year and the loss is millions of years, I think you are going to be sitting at this upper limit.

DR. BRICE: Except that the loss time scale is not going to be a million years at L = 1.05, for example, where you have atmospheric losses. If you have very fast diffusion close in, that is likely to enhance the proton loss.

DR. KENNEL: Then would there be any astronomical observations that you could make from fluxes of 100 MeV protons at the equatorial plane of Jupiter? This must be something that could be observed from a satellite. Are there any observational consequences on such a flux on Jupiter's surface?

DR. BRICE: I would have to put in a number for the flux in trying to calculate it.

DR. WHITE: For my clarification, could I say what you have done here? You have put an upper limit on the number of protons, you have not explained the electrons in any way, and you have not put a number on what you would expect for the protons. Is that correct?

DR. THORNE: Well, we have argued that this is an absolute upper limit on protons on the basis of stable trapping in an unstable region out here.

DR. MEAD: Roughly 10^9 protons per cm^2 per sec at L = 2.

DR. THORNE: Probably the protons are near this upper limit just because the injection time scales are much shorter than loss time scales.

DR. WHITE: Can you really say that? You don't know how the electrons get there.

DR. THORNE: This is on the basis that the electrons are diffusing in from the outer boundary and getting into $L \approx 1.5$.

DR. BRICE: In a year...

DR. THORNE: And, therefore, the assumption is that the protons must also have access to the inner zone.

DR. WHITE: But you have no idea of what this mechanism is, so you have no idea of whether it applies to protons or not.

DR. THORNE: If it were atmospheric turbulence, 1 m/sec random velocities in the atmosphere would produce electric fields of 10^{-3} V/m. Now, 1 m/sec is a very small velocity. In Jupiter, one could have velocities of hundreds of meters per second, and the resulting electric fields would be quite considerable in causing diffusion in this region.

DR. MEAD: I would like to ask about this L^{-3} portion on Figure 3. The energy conserving the first invariant is L^{-3}. Doesn't the flux, though, depend somewhat on the kind of mechanism you have to bring the particles in?

DR. THORNE: No. Any diffusion mechanism comes directly from the diffusion coefficient, regardless of what the diffusion coefficient is. It depends on the fact that μ is conserved.

DR. CORONITI: If you buy the physics of this stably trapping limit as an absolute filter for fluxes that you can get into the inner radiation belt and you realize that the solar wind conditions, energetic densities, and fluxes can vary by a factor of 10 or even larger during storms, you begin to understand why the synchrotron radiation is so constant; and you just can't get much more flux into the synchrotron belts than is permitted by the stably trapping limit. At IO's orbit, where the crossover is, the flux of energetic electrons can vary quite a bit. So, it is not unreasonable that Io shows strong solar wind control and the synchrotron emission doesn't, because this mechanism will keep that electron flux inside the synchrotron belt reasonably constant. This is a pretty reasonable clue that something like this is going on.

DR. BRICE: The energy threshhold for this is dependent on the plasma density, which at Io could vary, but the flux level is independent of the plasma density. While the plasma density could vary, it couldn't change the stable flux.

WAVE PROPAGATION IN THE MAGNETOSPHERE OF JUPITER

H. B. Liemohn*

INTRODUCTION

Exploration of the outer solar system in the coming decade is an exciting new step in space research due to the current lack of detailed information about the local environments around the planets and their satellites. The magnetosphere around Jupiter will be of special interest in view of its apparent similarity with the terrestrial magnetosphere. In situ observations by flyby missions will provide extensive new knowledge about the particles and fields in the magnetoplasma surrounding Jupiter and its Galilean satellites. The region is expected to contain intense local radio noise of natural origin which may be utilized as remote indicators of the various physical processes occurring in the medium. The purpose of this research is to develop a systematic procedure for identifying the spatial regimes of various modes of propagation that may be encountered by flyby missions to Jupiter. (Reference Liemohn and Kenney, 1971)

Most of our general knowledge about the characteristics of the magnetosphere surrounding Jupiter has been derived from the properties of its decimeter radiation (0.3-30 GHz). These radio observations and their theoretical analysis have been refined and reviewed extensively (Carr and Gulkis, 1969; Dickel et al., 1970; and Warwick, 1970) in the last few years so that a fairly clear set of basic parameters about the magnetosphere has been established. It seems clear that this radio noise is due to synchrotron emission from radiation belt particles trapped in a dipolar magnetic field that is corotating with the planet. There are significant deviations in the dipole shape to suggest the possibility of a small quadrupole moment or other local anomaly. From theoretical model calculations, the trapped radiation densities in Jupiter's magnetosphere are approximately three orders of

*Environmental Sciences Laboratory, Boeing Scientific Research Laboratories, Seattle, Washington 98124

magnitude greater than those of Earth. However, these energetic particles are not expected to be the primary ingredient in the plasma distribution around the planet.

As in the terrestrial magnetosphere, the plasma around Jupiter is expected to consist of quasi-thermal particles in diffusive equilibrium. Some hypothetical models of this plasma distribution (Melrose, 1967; Gledhill, 1967; and Ioannidis and Brice, 1971) have been deduced on the basis of known physical properties of Jupiter and its similarity to Earth. The primary source of the plasma is thought to be ionospheric photoelectrons (10-30 eV) and diffusing thermal protons (<5 eV). As a consequence of the rapid rotation of Jupiter, most models that have been derived have a characteristic pancake shape with high densities only in the vicinity of the zenographic equator.

These models of the Jovian magnetic field and plasma distribution provide an unusual propagation medium for *local* radio noise. Again, by analogy with Earth, the Jovian magnetosphere is expected to contain enormous amounts of radio noise at frequencies near the local plasma and cyclotron frequencies due to plasma instabilities, natural particle-emissions, solar wind disturbances, and surface lightning. The signature of this local radio noise is an important tool for remote sensing of regions well removed from the spacecraft. The selection of proper frequencies and bandwidths for the space probe experiments requires detailed numerical models of the magneto-ionic medium. Furthermore, the interpretation of the observed signal characteristics will require a study of propagation properties in regions adjacent to the detector.

In order to systematically study the propagation properties of this magnetoplasma, the well-known Clemmow-Mullaly-Allis (CMA) diagram of plasma physics has been utilized. This diagram divides the complex modes of propagation into various regions or ponds in which a characteristic type of propagation is readily identified and analyzed. For specified propagation frequencies and selected magnetoplasma models, similar propagation ponds can be identified in the configuration space around the planet. Loci of propagation cutoffs and resonances are clearly identified and assist in determining the distribution of radio noise. These properties provide a useful basis for speculation about the distribution of local radio noise and its relevant source mechanisms.

Magnetoplasma Models

Theoretically, the main magnetic field of Jupiter is quite adequately represented by a dipole in this application. There are significant deviations in the shape of the field to suggest the possibility of small quadrupole moments or local anomalies, but these will be ignored here. Also, the dipole is undoubtedly tilted and not centered at the centroid of the planet, but this effect will also be ignored for lack of sufficient detailed knowledge about these corrections. The magnitude of the dipole moment is still in doubt by as much as a factor of three, but the best estimate at present gives an equatorial surface field of about 10 gauss.

Several models have been proposed for the Jovian plasma distribution but only two of them will be considered here (Gledhill, 1967 and Ioannidis and Brice, 1971). These models are characterized by an ionospheric source for the thermal plasma particles and a rapidly corotating Jovian magnetosphere, which causes the plasma to be confined near the zenographic equatorial plane. However, the physical processes invoked to generate these models are quite different and the details of their distributions are consequently dissimilar.

In the Gledhill model, the cold ionospheric plasma is assumed to diffuse slowly up field lines until it crosses the threshold point where centrifugal force pulls it rapidly toward the equatorial plane. The limiting density at the equatorial plane is estimated to be that which gives rotational kinetic energy for the plasma that is comparable with the magnetic energy density of the main field. For a dipole magnetic field with a surface strength of 10 gauss, this gives an enormous upper limit of $10^{13}\ L^{-8}$ particles/cm^3, where L is expressed in Jovian radii. For the analysis presented here, a more realistic equatorial plasma distribution of the form $10^6\ L^{-4}$ particles/cm^3

has been assumed. Gledhill assumes this cold plasma has a Maxwellian distribution with a temperature of 1800°K that causes diffusion away from the equatorial plane. Iso-intensity contours for the plasma density and magnetic field intensity are shown in Figure 1. The sharp decrease in plasma density away from the equator is terminated abruptly by a floor of 0.1 particles/cm^3, which has been proposed (Ioannidis and Brice, 1971) as the lower limit of the plasma density due to photoelectron generation throughout the Jovian magnetosphere.

The plasma distribution model by Ioannidis and Brice assumes that the magnetosphere is populated by photoelectrons that have boiled off the top of the ionosphere. These photoelectrons are assumed to have energies of about 10 eV, so that the thermal energy of the plasma is considerably greater than that by Gledhill. This outward flux of photoelectrons from the ionosphere causes ambipolar diffusion of thermal protons. The resulting diffusive equilibrium source density of quasi-thermal plasma is about 0.1 particles/cm^3 just above the ionosphere and increases radially outward. The density distribution is severely limited by recombination of the electrons with ions and untrapping due to overloading the magnetic field. Recombination limits the maximum density to approximately 10^3 particles/cm^3 and the dipole magnetic field reduces this upper limit further beyond about 15 Jovian radii. The net effect of these physical considerations is a plasma model that is sharply peaked near 10 Jovian radii with a maximum density of only 100 particles/cm^3. The relatively higher photo-electron energies yield a distribution that falls off more slowly away from the zenographic equatorial plane. Iso-intensity contours of the plasma density model and the magnetic field strengths for the centered dipole are shown in Figure 2. Again, the plasma density is assumed to have a lower limit of 0.1 particles/cm^3.

Although these two magnetoplasma models have not been verified experimentally, they provide a reasonable basis for estimating the propagation characteristics of the local radio noise around the planet Jupiter. To evaluate the wave propagation properties, these plasma densities must be converted to the plasma frequency $\Pi_e = (4\pi Ne^2/m)^{\frac{1}{2}}$ and the magnetic field strengths B must be converted into the electron cyclotron frequency Ω_e = eB/mc and the ion cyclotron frequency Ω_i = eB/mc. The mode characteristics will be determined by conventional magneto-ionic theory for a cold plasma.

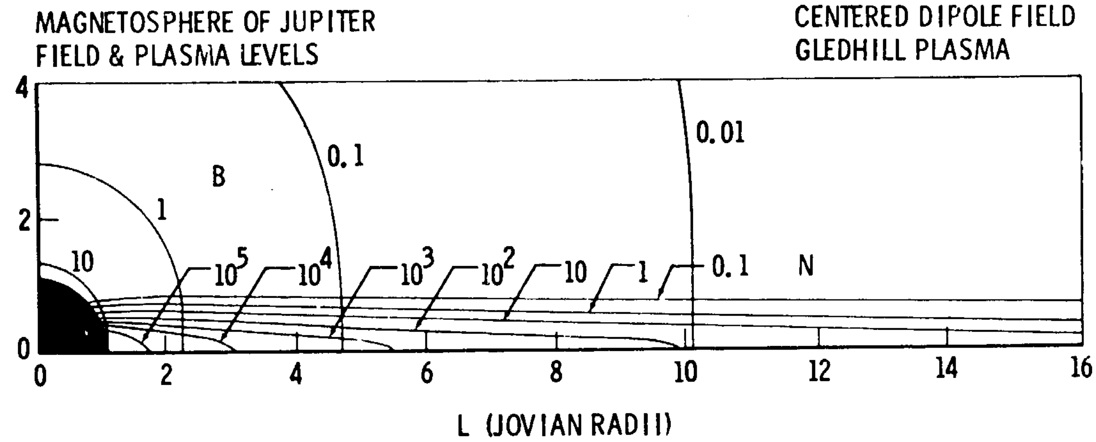

Figure 1. Gledhill (1967) Magnetoplasma model for the Jovian magnetosphere. Iso-intensity contours are presented for the plasma density N (particles/cm^3) and magnetic field B (gauss). See text for details of the model.

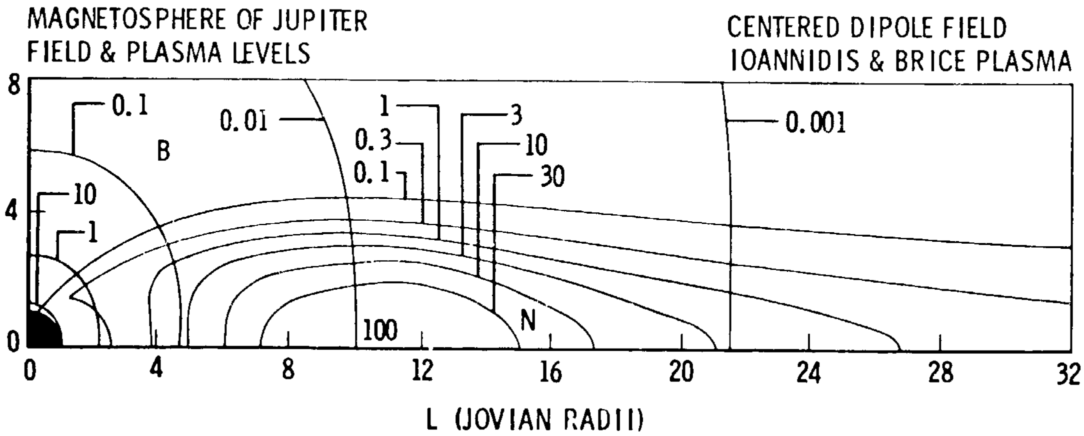

Figure 2. Ioannidis and Brice (1971) Magnetoplasma model for the Jovian magnetosphere. Iso-intensity contours are presented for the plasma density N (particles/cm^3) and magnetic field B (gauss). See text for details of the model.

The CMA Diagram

In order to systematically summarize the propagation properties for these magnetosplasma models, spatial analogs of the well-known Clemmow-Mullaly-Allis (CMA) diagrams of plasma physics have been constructed. The CMA diagrams (Stix, 1962), shown in Figure 3, identify the various frequency regimes in which different modes of propagation occur. The frequency parameters for the medium, Ω_e and Π_e are normalized to the propagation frequency, ω. The loci that divide the parameter space Ω_e^2/ω^2 and Π_e^2/ω^2 are defined by propagation cutoffs and resonances. At cutoffs, the index of refraction vanishes, terminating the propagation of a particular mode and reflecting its wave energy. At wave-particle resonances, the index effectively becomes infinite terminating the mode by absorbing its energy. For example, the line R = 0 is a cutoff for the right-hand mode of propagation that divides region I and region II; the S = 0 line between regions II and III is the upper hybrid resonance. Other curves of special note are the lines R = ∞ and L = ∞, which correspond to the electron and ion-cyclotron resonances. For a complete account of the wave mode genera and a mathematical description of the physics defining these loci, the reader is referred to the literature (e.g., Stix, 1962; Allis et al., 1962).

The closed curves in each of the regions in the CMA diagram represent phase velocity surfaces that are characteristic of the modes in that part of the parameter space. The orientation of these surfaces has been selected to correspond to a magnetic field strength directed vertically along the cyclotron resonance axis. The R and L associated with these diagrams refer to right-hand and left-hand circular polarization, respectively, for waves propagating along the magnetic field; the O and X symbols denote ordinary and extra-ordinary modes of propagation perpendicular to the direction of the magnetic field.

Some of the regions in this diagram are particularly well-known because they describe modes of propagation that are encountered in the terrestrial magnetosphere. Clearly, region I describes propagation where the plasma and field have a relatively small effect on the electromagnetic signals.

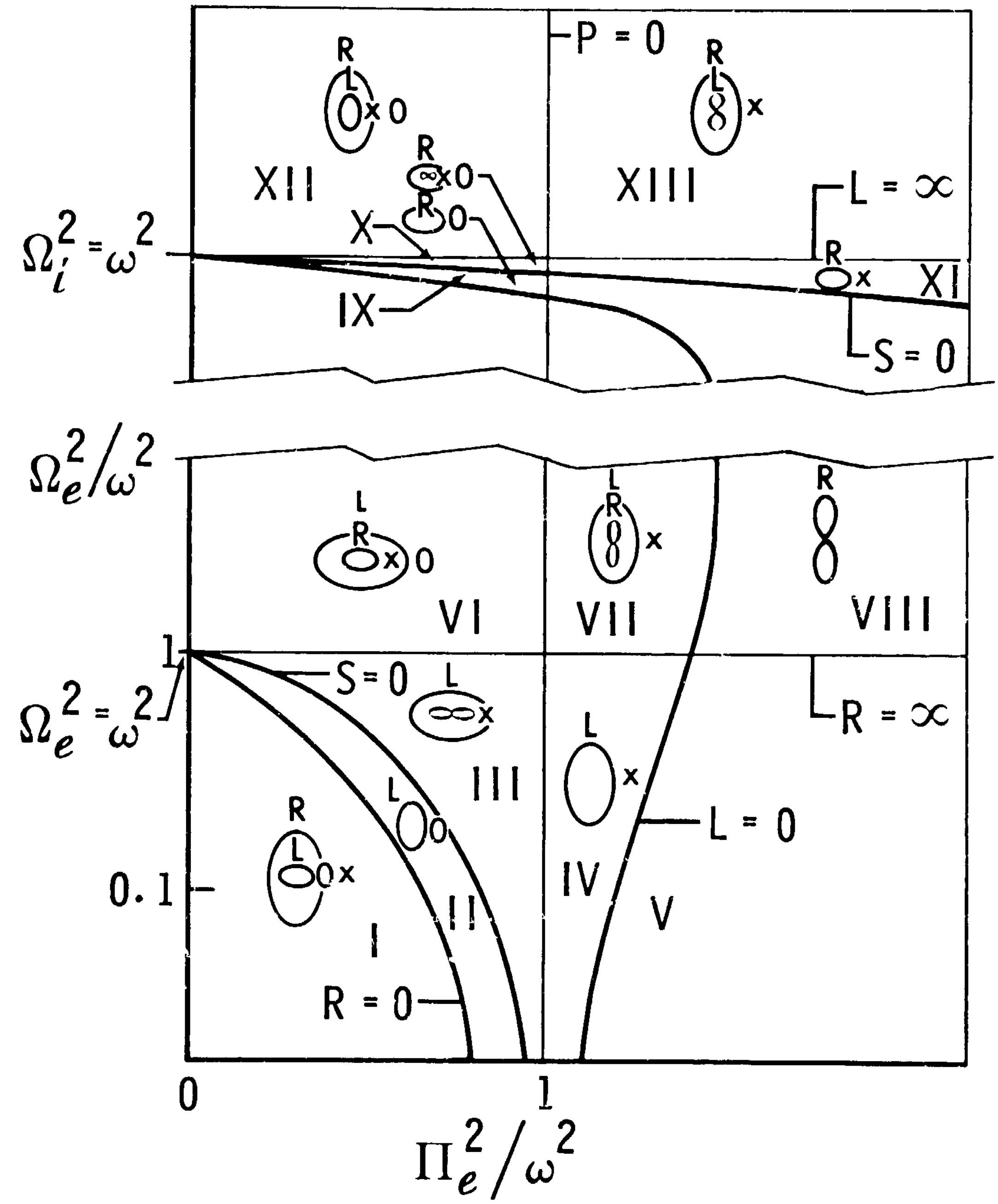

Figure 3. The Clemmow-Mullaly-Allis diagram for plasma wave modes. Loci for propagation cutoffs (R = 0, L = 0, and P = 0) and resonances (R = ∞, L = ∞, and S = 0) are shown as functions of the electron-cyclotron frequency Ω_e and plasma frequency Π_e normalized to the propagation frequency ω. Characteristic phase velocity surfaces of the modes in each region are oriented for a magnetic field directed along the vertical Ω_e axis.

The upper hybrid resonance between regions II and III is well-known as a source of considerable terrestrial radio noise. Region VIII is well-known because it describes the VLF whistler propagation along geomagnetic field lines; similarly in region XIII the L mode describes propagation of ULF whistlers (Pc1 micropulsations) along geomagnetic field lines.

Plasma Propagation Ponds

The phase velocity surfaces in the CMA diagram may be construed as wave fronts emanating from a point source analogous to waves caused by a pebble dropped into a water pond. Thus, it is convenient to think of the various regions, I-XIII, as plasma propagation ponds in which a certain specified shape of wave surface is generated.

The construction of plasma propagation ponds in the configuration space adjacent to Jupiter follows directly from the foregoing considerations of the CMA diagram. For a specified frequency of propagation, the distribution of cyclotron and plasma frequencies defines the loci of propagation cutoffs and resonances analogous to those in the CMA diagrams; and the propagation regimes may be labeled I-XIII, depending on the region of parameter space under consideration. In Figures 4, 5, and 6 propagation ponds for the Gledhill model have been constructed for frequencies from 10^6 Hz to 10 Hz; similarly, Figures 7, 8, and 9 describe the propagation ponds for the Ioannidis and Brice magnetoplasma model. These diagrams provide a useful basis for estimating the important frequency bands and spatial distribution of radio noise in the Jovian magnetosphere. In addition, the spatial distribution affects the energetic particle population due to a variety of plasma instability mechanisms which cause energy exchange and pitch angle scattering.

Discussion of Distinctive Propagation Features

Since both magnetoplasma models exhibit strong gradients in plasma density around the zenographic equator, it is not unexpected to have similar abrupt changes in the propagation properties near the equatorial plane. Furthermore, the use of a centered dipole magnetic field model places

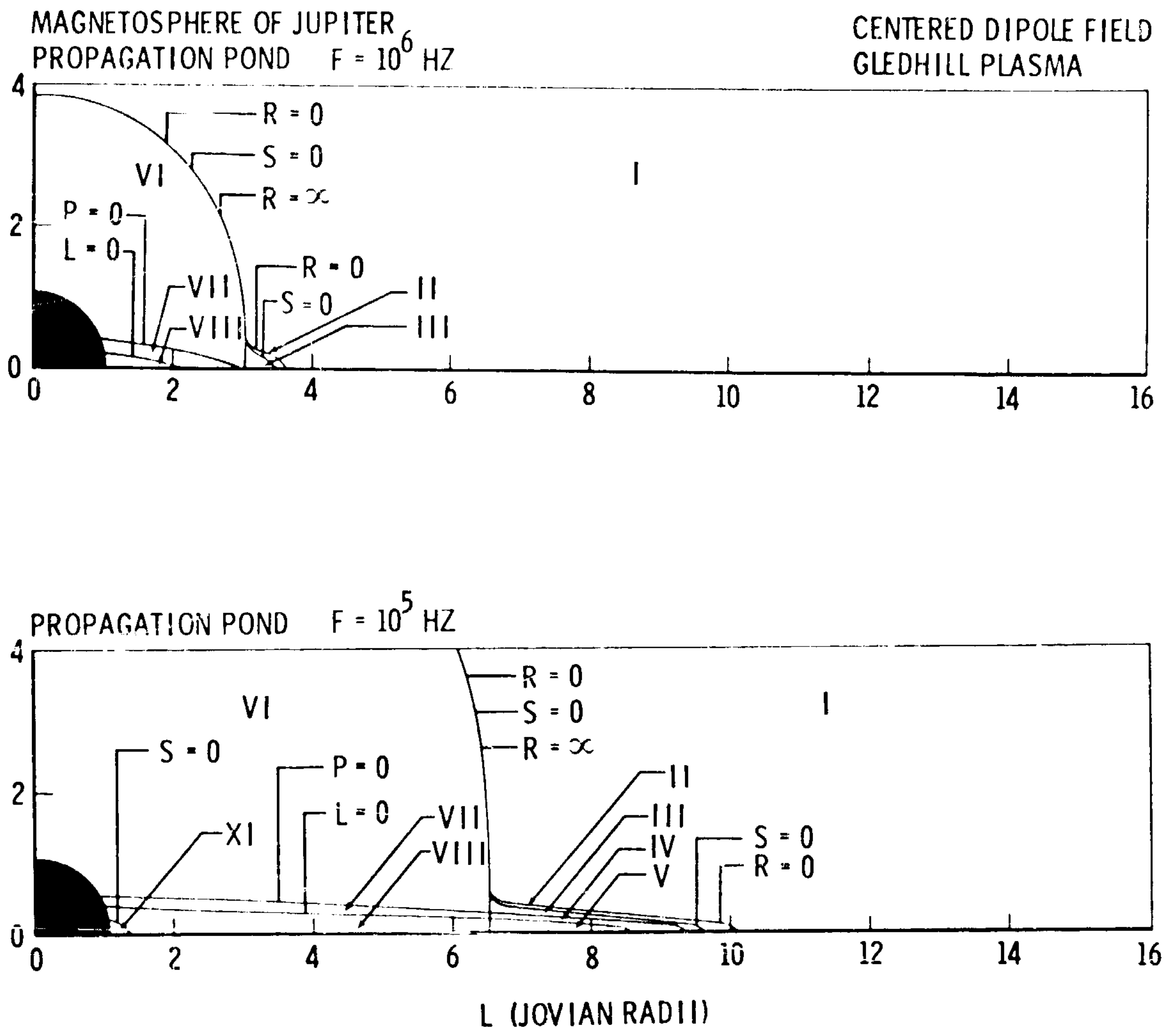

Figure 4. Configuration-space CMA diagram for the Gledhill model of the Jovian magnetosphere. a) Propagation frequency of 10^5 Hz; b) propagation frequency of 10^5 Hz. See Figure 3 for wave mode characteristics corresponding to region designation (Roman numerals).

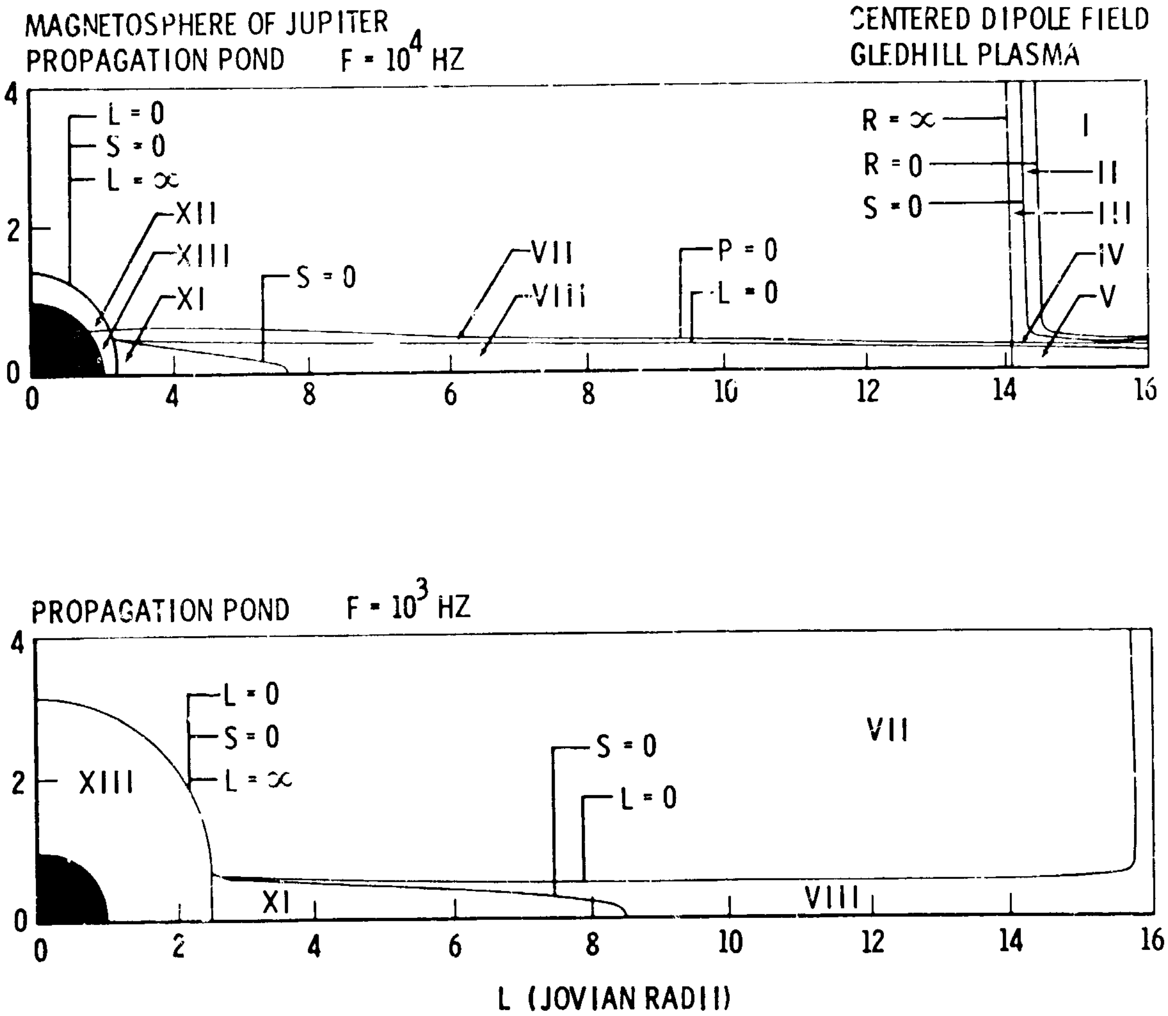

Figure 5. Configuration-space CMA diagram for the Gledhill model of the Jovian magnetosphere. a) Propagation frequency of 10^4 Hz; b) propagation frequency of 10^3 Hz. See Figure 3 for wave mode characteristics corresponding to region designation (Roman numerals).

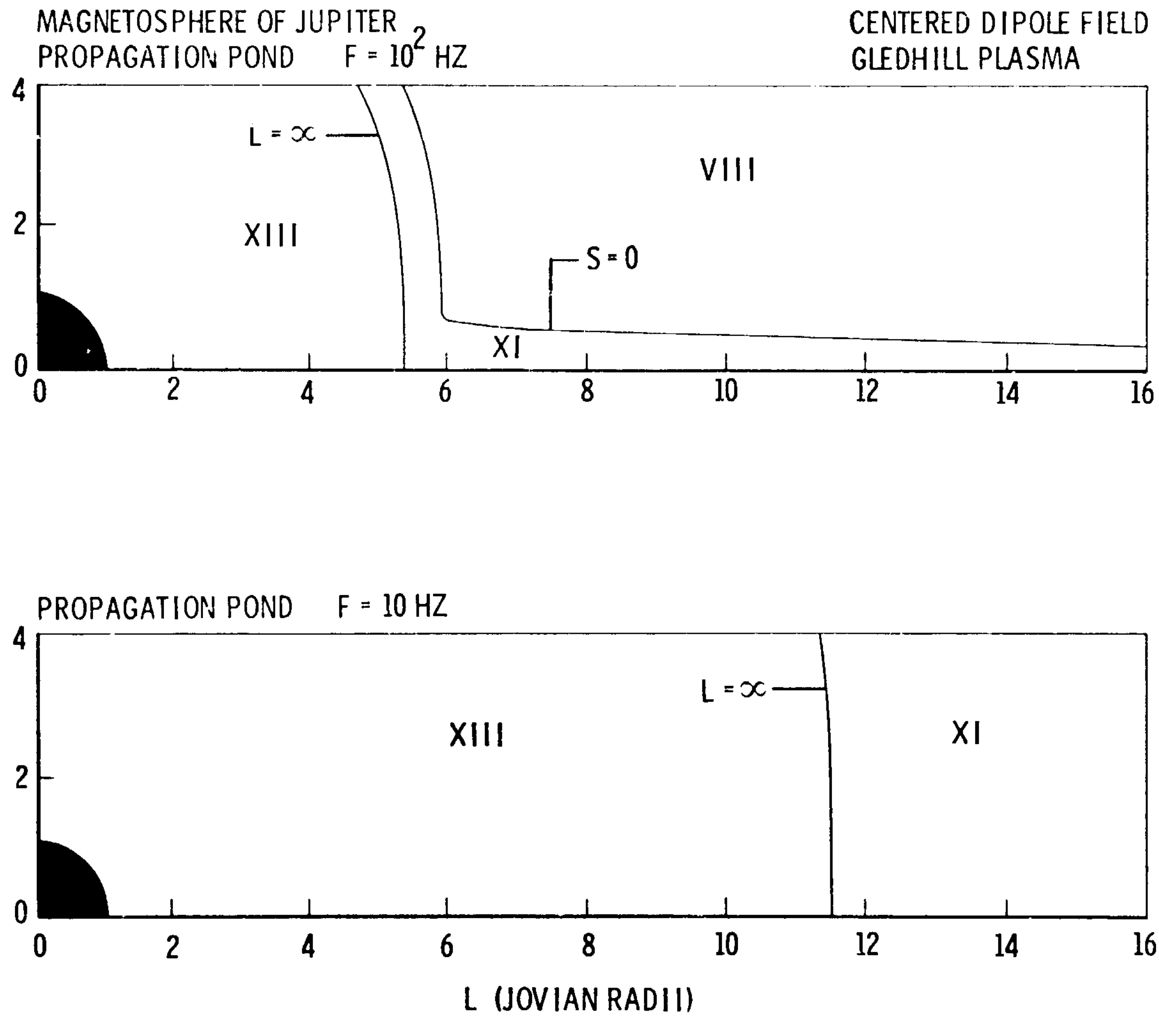

Figure 6. Configuration-space CMA diagram for the Gledhill model of the Jovian magnetosphere. a) Propagation frequency of 10^2 Hz; b) propagation frequency of 10 Hz. See Figure 3 for wave mode characteristics corresponding to region designation (Roman numerals).

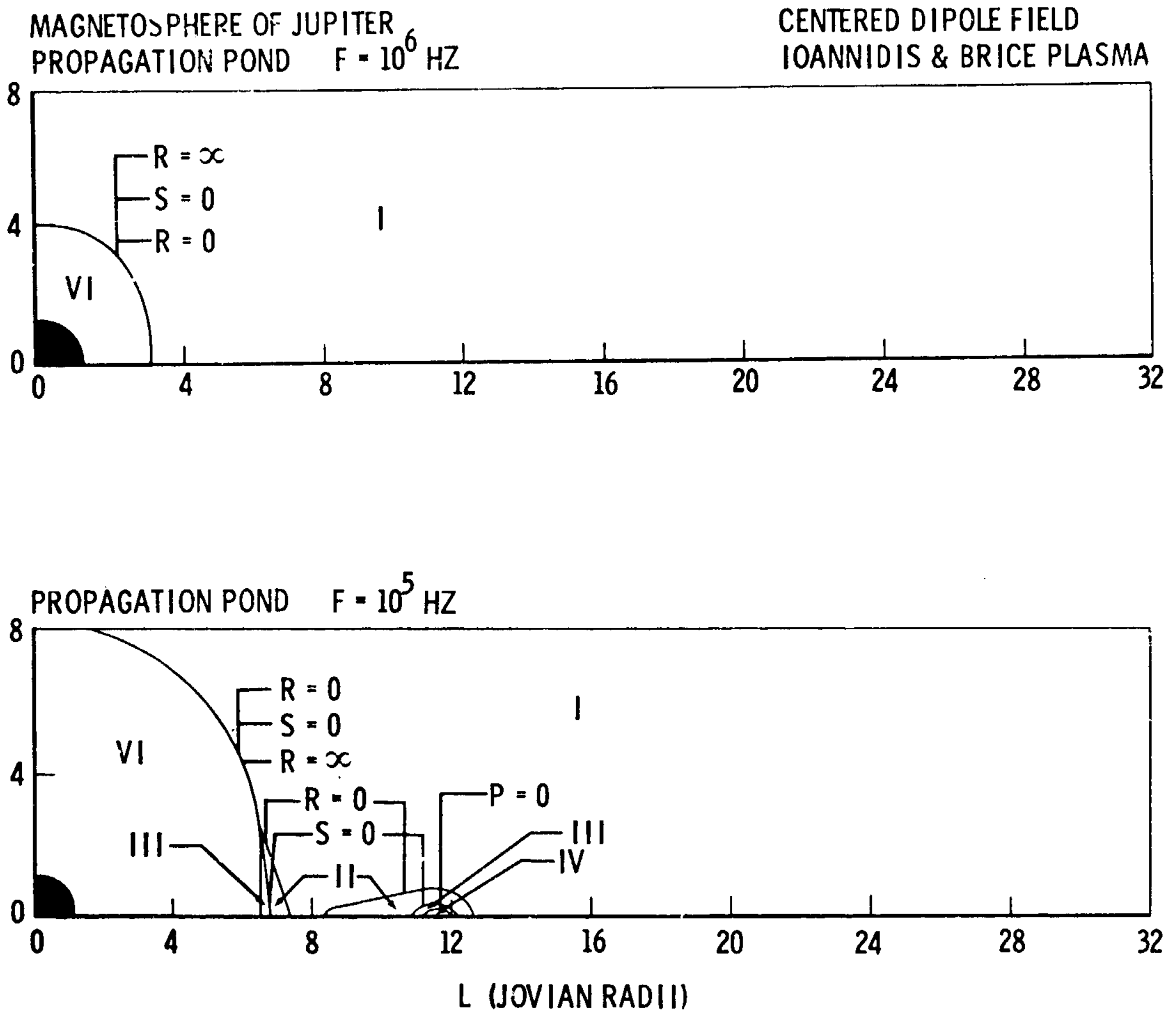

Figure 7. Configuration-space CMA diagrams for the Ioannidis and Brice model of the Jovian magnetosphere. a) Propagation frequency of 10^6 Hz; b) propagation frequency of 10^5 Hz. See figure 3 for wave mode characteristics corresponding to region designation (Roman numerals).

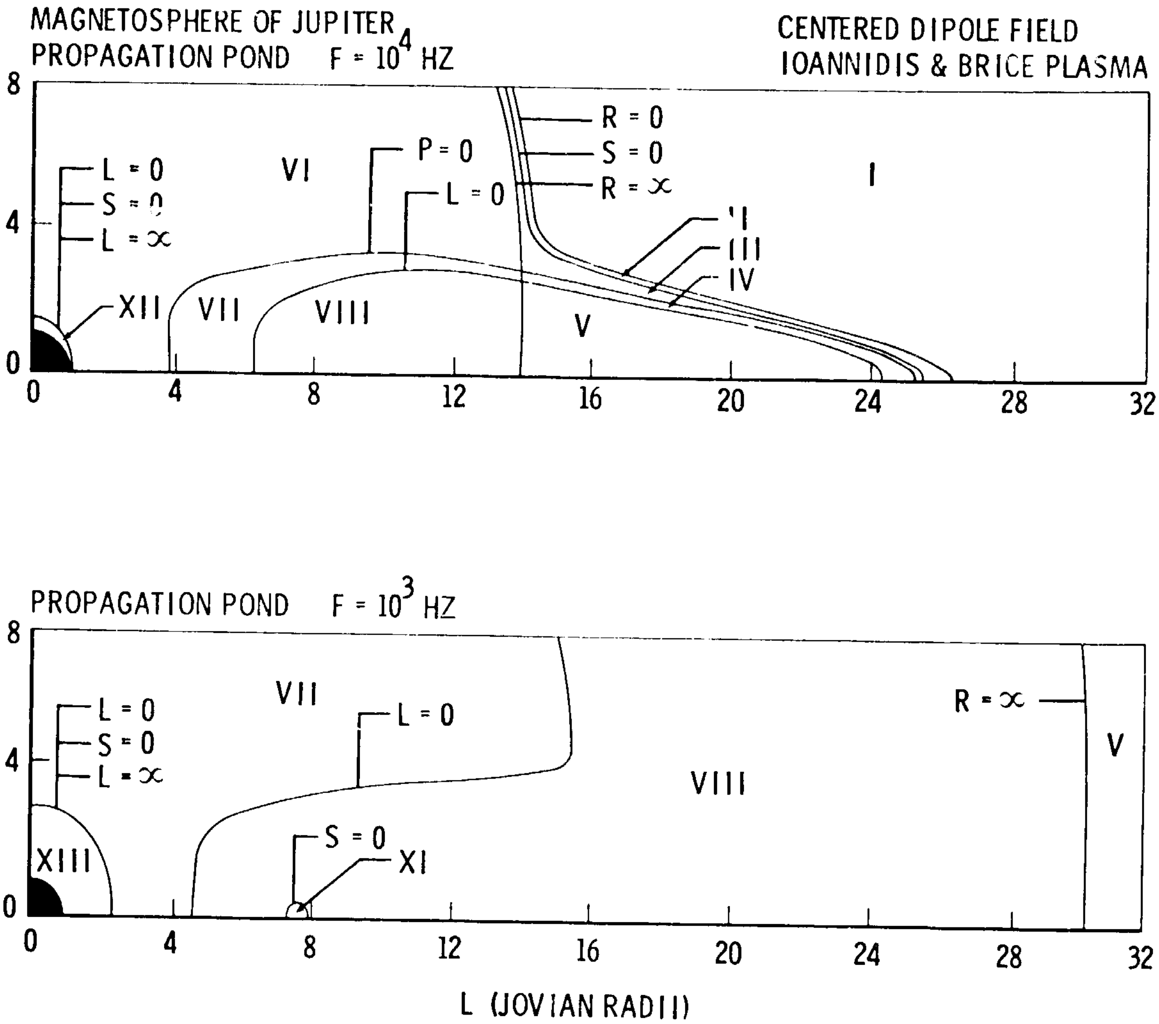

Figure 8. Configuration-space CMA diagrams for the Ioannidis and Brice model of the Jovian magnetosphere. a) Propagation frequency of 10^4 Hz; b) propagation frequency of 10^3 Hz. See Figure 3 for wave mode characteristics corresponding to region designation (Roman numerals).

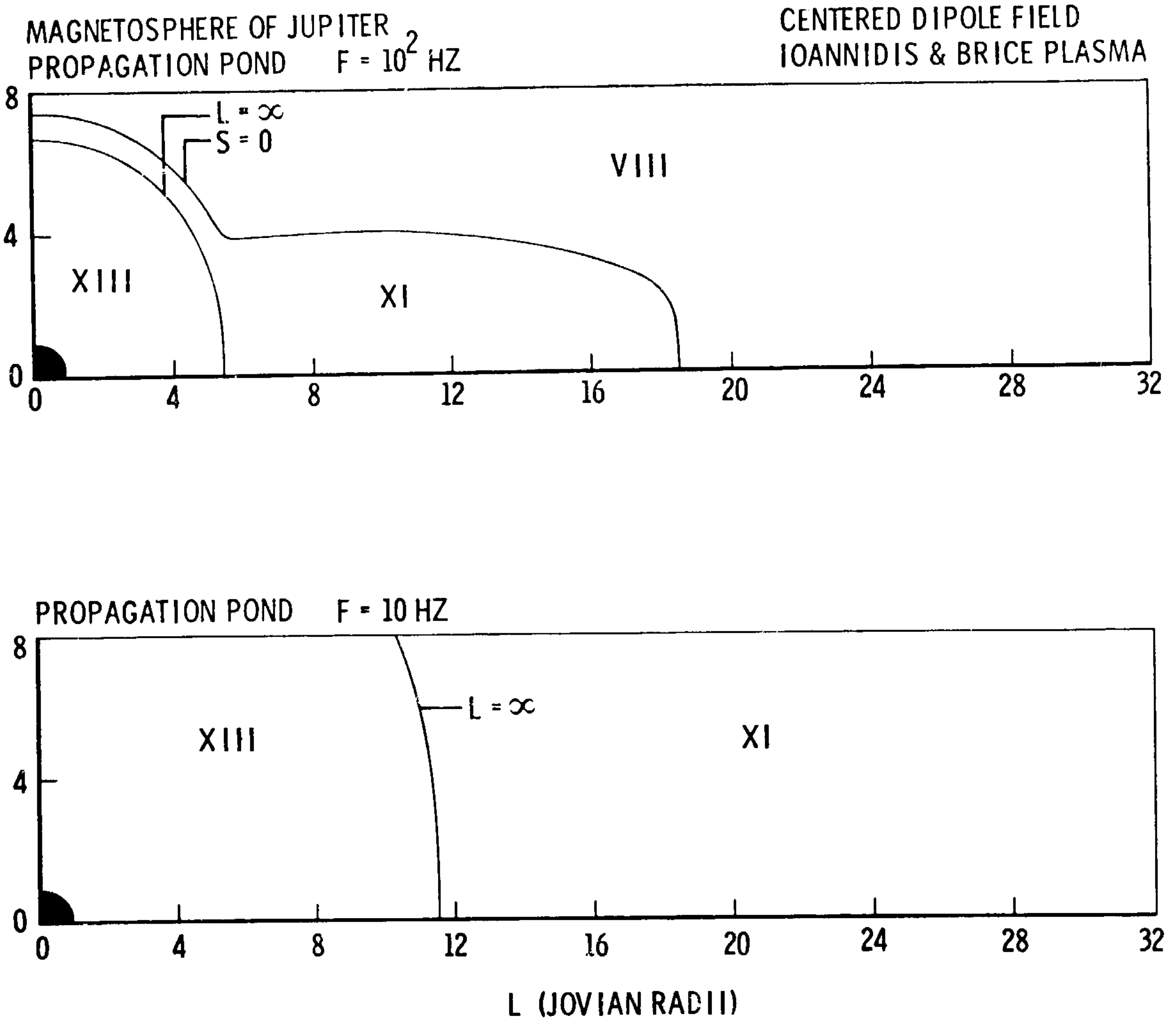

Figure 9. Configuration-space CMA diagrams for the Ioannidis and Brice model of the Jovian magnetosphere. a) Propagation frequency of 10^2 Hz; b) propagation frequency of 10 Hz. See Figure 3 for wave mode characteristics corresponding to region designation (Roman numerals).

the cyclotron resonance contours at the same locations. Region VIII is particularly significant in that it is confined to a narrow region near the equatorial plane. Thus, the analog of the well-known terrestrial VLF whistlers, which propagate from one hemisphere to the other along magnetic field lines, do not occur in the Jovian magnetosphere. However, at lower frequencies, region XIII does envelop the entire planet so that a Jovian analog of the terrestrial ULF whistler (micropulsations) can occur and propagate along inter-hemisphere magnetic field-line paths. At still lower frequencies, all the usual terrestrial micropulsation modes may be expected to propagate throughout the Jovian magnetosphere.

There are some unusual differences between the propagation properties of the two magnetoplasma models as well. For example, the Gledhill model has a region V near the zenographic equator where no electromagnetic propagation can occur. Such dead zones should be particularly easy to detect with broadband receivers. Adjacent to region IV and V is the upper hybrid resonance frequency between regions II and III which should be quite noticeable as the propagation modes change abruptly. In region VI, both modes propagate in all directions so that the wave energy can be scattered readily and will not be guided in typical whistler fashion along the magnetic field.

The Ioannidis and Brice magnetoplasma has its own peculiar propagation properties due to the strongly peaked plasma density in the vicinity of 10 Jovian radii. This behavior provides a distinctive propagation pattern in the general area of the zenographic equator between 8 and 16 Jovian radii. Unusual contours of the upper and lower hybrid resonance bands are to be anticipated if this model prevails. This model also permits an extended region VIII surrounding the zenographic equator, which will permit considerable guided propagation with attendent wave particle interactions.

It should be re-emphasized here that these propagation regimes are based on elementary models of the medium. The effects of noncentered and distorted dipole fields, and more exotic plasma distribution models will significantly alter the shape of these propagation mode boundaries. However, the principle used here will apply in any case, and the models employed here are the best currently available.

Radio Noise Regimes

The spatial propagation regimes shown in Figures 4 to 9 provide a useful basis for speculation about the local radio noise that may be anticipated around Jupiter. The variety of propagation ponds located near the zenographic equator strongly suggests that radio noise is most strongly concentrated there. Whistler mode noise near Ω_c can be expected throughout regions VIII, VII, and VI with relative diminishing intensity, respectively. In region VIII, the field aligned propagation lends itself to wave particle amplification so that strong signals should occur near the equator. The analog of the terrestrial VLF hiss and chorus is undoubtedly generated here. However, this noise does not follow field-line (whistler mode) paths to the surface of Jupiter. Similarly, surface lightning signals merely illuminate the local region VI above the source without guided propagation.

By analogy with noise in the terrestrial magnetosphere, the upper hybrid resonance between regions II and III should be a very noisy source of electromagnetic energy. Since no propagation can occur in region V, the shape of this dead zone should provide a significant test of any proposed magnetoplasma model.

At low frequencies region XIII completely surrounds the planet, suggesting a propagation medium analogous to that around the Earth. Thus, substantial amounts of hydromagnetic wave noise may be expected if local source mechanisms are available at these frequencies. However, the distant location of the boundaries between the solar wind and the Jovian magnetosphere may significantly reduce the amount of hydromagnetic wave energy that is coupled into the lower regions of the magnetoplasma adjacent to the planet.

Since the plasma gradients in the Jovian magnetosphere are anticipated to be very large, substantial mode coupling can be anticipated at resonance and cutoff boundaries between the propagation ponds. For example, there will be a significant build-up of transverse propagation in region III as energy traverses the upper hybrid resonance. Similarly in region XIII where both modes ordinarily propagate, a source for either mode will couple energy to the other at density discontinuities. This complicated behavior necessitates simultaneous analysis of several frequency bands for complete interpretation of the observed signals.

Wave-Particle Interactions

A principal source of the local electromagnetic noise around Jupiter is expected to be wave-particle interactions. However, detailed hot plasma analysis for possible interactions is beyond the scope of this paper. Nevertheless, the available modes of propagation permit some useful speculation based on experience with such interactions in the terrestrial magnetosphere (e.g., Kennel and Petschek, 1966; Liemohn, 1967; Kennel et al., 1970; and Cornwall et al., 1970) and the solar wind (e.g., Kennel and Scarf, 1968 and Scarf, 1970). Of course the extent of the interactions depends entirely on the shape of the phase space distribution of the energetic particles.

The most obvious interaction is the cyclotron resonance energy exchange between electrons and waves near Ω_e and between protons and waves near Ω_i. These interactions are allowed in regions VI-VIII and XII-XIII, respectively, which may be easily located in Figures 4 to 9. This interaction in the terrestrial magnetosphere accounts for amplification of VLF and ULF whistlers (Liemohn, 1967) and an extensive amount of radio noise such as VLF hiss and chorus and ULF signals in the Pc1 and Pi1 bands. At Jupiter similar amplification is anticipated. However, because there is no guidance in region VI, signals cannot echo significantly, and no strong build-up of wave energy is expected around Ω_e due to coherent signal amplification.

However, there will undoubtedly be very strong signal intensities due to incoherent cyclotron and Cerenkov radiation from energetic electrons (Liemohn, 1965). Such emissions will radiate generally from the vicinity of the equator where the strongest amplification occurs. Of course, the signal energy will spread out as it propagates into region VI. The level of noise will depend on the energy spectrum and pitch angle distribution of the energetic electrons in the medium.

Since region XIII completely dominates the propagation at low frequencies below Ω_i, all the processes of emission, amplification, and particle precipitation that occur in the terrestrial magnetosphere may be expected around Jupiter as well. Thus, the energetic proton population and the hydromagnetic wave energy must achieve an equilibrium state (Kennel and Petschek, 1966). Large amplification of coherent (left-hand whistler mode) signals is undoubtedly present so that large amplitude spikes of guided energy are likely to occur. The background noise level is also probably substantial by analogy with the terrestrial environment. The ion-cyclotron turbulence that is evidently responsible for proton precipitation in the terrestrial case (Cornwall et al., 1970), is undoubtedly present in the Jovian magnetosphere. Its extent depends not only on the phase space distribution of energetic particles, but also on the existence of a well-defined discontinuity (plasmapause) in the background plasma.

There are probably other plasma instabilities in the magnetosphere that contribute to the overall wave-particle equilibrium. One of them may be the nonresonant firehose instability at low frequencies around Ω_i (Kennel and Scarf, 1968). This instability occurs when the centrifugal force due to parallel particle pressure overcomes magnetic tension and perpendicular particle pressure resulting in radial drift. The interaction is band-limited and depends critically on both the electron and proton pitch angle anisotropies.

Conclusion

The Jovian magnetosphere offers an exciting new environment for the study of radio wave propagation. There are many similarities with the terrestrial magnetosphere but there are several significant differences as well. The concentration of plasma in the equatorial plane makes this region of vital importance for radio observations with flyby missions. Local radio noise around the electron-cyclotron frequency will probably differ appreciably from its terrestrial counterpart due to the lack of field-line guidance. On the other hand, the hydromagnetic wave properties at frequencies near Ω_i and below will probably be quite similar to the terrestrial case.

The method of mapping the CMA diagram into configuration space around the planet offers considerable visibility for the possible mode structure. The magnetoplasma models used here provide a good basis for this initial study, and subsequent revisions with more exotic distributions are readily incorporated into this method of analysis. One important improvement would be the introduction of a tilted and noncentered dipole. Since the plasma distribution is presumably confined by centrifugal forces to the zenographic equator, this misalignment of field and plasma would present several new regions of propagation. Such a computer study is planned in the future.

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DISCUSSION

DR. SCARF: I would just like to comment that in the model with the temperature of 200,000 degrees, I would think that the warm plasma modes would be much more important than they are in the Earth's plasmasphere, where we are dealing with temperatures between 10 and 1,000 degrees.

DR. LIEMOHN: Right.

MR. BECK: Have you made any estimates of proton flux limits?

DR. LIEMOHN: No. I didn't feel I had a means of doing more than showing that there was an interaction region available.

A RESONANT INSTABILITY OF MODEL PROTON RADIATION BELTS IN THE JOVIAN MAGNETOSPHERE

Fritz Neubauer*

I would like to fill in some more information on the ion cyclotron instability and report on some calculations I have made. Of course, it is like taking spaghetti to Italy to go to this place here and talk about resonant instability, but I think it is worthwhile to put in some more information. I shall first talk on some other aspects of the ion cyclotron wave, which are essentially generated by low refractive indices and relativistic corrections, and then try to get some upper limits. The conclusions will be similar to those in the first talks today.

I shall here restrict myself to the left-handed wave mode, which close to the ion gyro frequency is called ion cyclotron wave. This wave can be unstable for a loss cone distribution of the ions. First, I have applied the usual mathematical perturbation technique to the dispersion relations, which, however, did not assume, as the other work did, that resonant particles are non-relativistic, and, in addition, that the refractive indices are large with respect to one, which is not fulfilled in some parts of the Jovian magnetosphere. The numerical results are then applicable to the case of propagation parallel to the magnetic field. This is a simplification, but one can show by fairly simple arguments that the instability growth rate goes down as one goes away from the field direction. There is a cone of propagation that is well known, and I just want to mention it.

The ion cyclotron wave is determined in its damping and growth characteristics by resonant particles--by protons and electrons. These resonant particles are found in momentum space on so-called resonant surfaces. In the classical case, these resonant surfaces are planes perpendicular to the magnetic field. In the relativistic case, they are hyperbolas of revolution around the magnetic field and there are some interesting properties in addition to the

*Goddard Space Flight Center, Greenbelt, Maryland 20771.

classical case. Both hyperbolas for the electrons and for the protons open in the direction of the wave propagation. One interesting thing is, for example, that the destabilizing particle species--protons in the case we are considering here--can also have velocities or momentum parallel to the wave propagation. These protons have a stabilizing effect, whereas in the classical case, every proton on the resonant surface contributes to instability. The stabilizing protons have energies larger than the classical gyrofrequency over the frequency times the rest energy (which is about 1 BeV). If the wave frequency is fairly close to the ion cyclotron frequency, this energy could be rather low, say, some BeV. I must add, I do not necessarily imply here that the proton energies are this large in our case, but I am only trying to get a consistent description of this type of instability.

I have shown an example (Figure 1) for these resonant surfaces in momentum space. Note that the abscissa goes to the left-hand side. It shows the parallel momentum in units of proton mass times velocity of light. The ordinate shows the perpendicular component. The case shown in Figure 1 would generally be called a classical case corresponding to a refractive index of 200, which in the equatorial plane of Jupiter is found somewhat outside L=10, according to the density model by Ioannidis and Brice.[1] X_i is shown as the gyrofrequency over the wave frequency. This parameter is used in magneto-ionic theory. We see here that the parallel momentum is essentially constant for low perpendicular momentum corresponding to the classical case (although this also is sometimes true for relativistic particles). Then, it bends around and passes through $P_{\parallel} = 0$. Also illustrated are the negative branches which go up to infinite energies. $X_i=2$, for example, means one-half of the gyrofrequency. The second curve corresponds to one-tenth of the gyrofrequency; the third curve corresponds to one-hundredth of the gyrofrequency. This is only shown to illustrate the resonance condition (which is somewhat more complicated than the classical case condition).

Applying this to Jupiter, I derived instability rates for the region in the equatorial plane with the Ioannidis and Brice density model, which is

[1] *Ioannidis, G. A., and Brice, N. M.; "Plasma Densities in the Jovian Magnetosphere: Plasma Slingshot or Maxwell Demon?;" Icarus; Vol. 14; No. 3; pp. 360-373; 1971.*

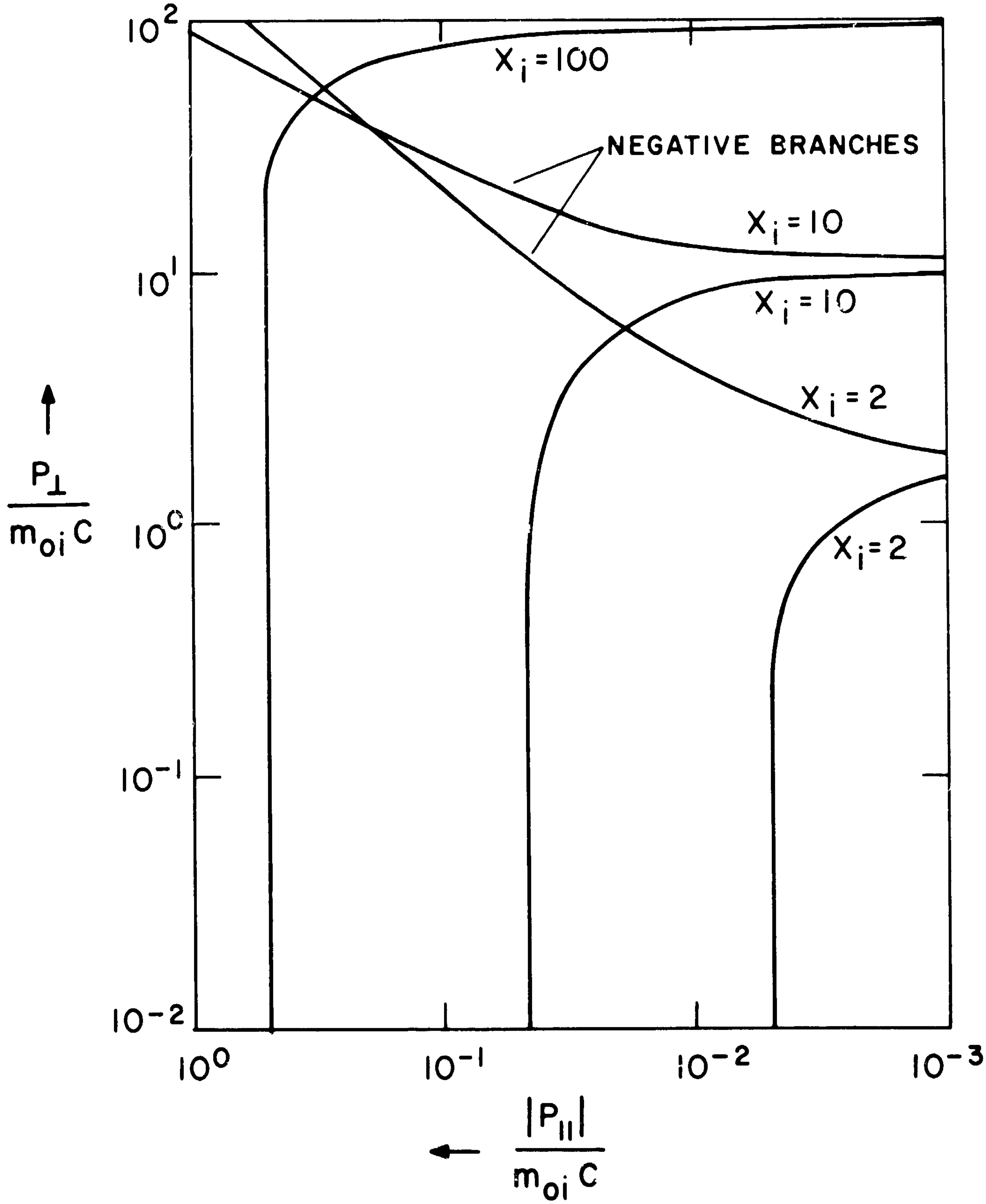

Figure 1. Resonant Surfaces in Momentum Space

the only physically self-consistent model, so I don't think there is any justification to use any other model. The instability region is near the equator because the resonant energy is a minimum there. My calculations pertain to that region. In the case of Jupiter, it is even more pronounced because the density goes down going away from the equator along the field line.

The next thing I am going to do is to discuss the upper limits from these results, essentially using the same mechanism as Kennel[2] pointed out today. With the magnetospheric laser mechanism, we can get an upper limit if we use the anisotropies given by the solution of the diffusion equation for simple pitch-angle diffusion in the Kennel and Petschek paper[3]. In Jupiter's case, it is probably not applicable in this simple way (at least in the region where the resonant energies go up very quickly) or, in other words, where the refractive indices go down very quickly, it is probably more difficult. I use (for the model proton belts) a distribution function in momentum space given by $f_i = C_i \sin^{2n} \alpha \, (\gamma - 1)^{-m} \, \gamma^{-1} \, (\gamma^2 - 1)^{-\frac{1}{2}}$, where α is the pitch-angle and $\gamma - 1$ is the kinetic energy in units of the rest energy. The differential energy spectrum is simply $N(E)dE \propto (\gamma - 1)^{-m} dE$. Using f_i, I have then calculated instability growth-rates as a function of frequency and distance for several pairs of m,n. The results are shown in Figure 2.[4] Because of lack of time, I was using the anisotropy given by Kennel and Petschek at L~15, and I just used the exponent for the pitch-angle distribution corresponding to this anisotropy of n=0.1. At L~5 it has the consequence of overestimating the limiting flux by about two. The wave gain in the instability region has to compensate all the losses, propagation losses, damping losses, etc. I assumed a necessary spatial growth-rate at the equator by a factor one over 1 R_J, where any L dependence doesn't actually play an important role because I am discussing the limited L-range from 5 to 10 or so. In addition, m=3 and the maximum growth rate as a function of frequency was used.

What I get now is somewhat more than Dr. Brice got. It is a density or a particle flux which essentially gives an energy density of the same

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[2] *Kennel, Charles; "Stably Trapped Proton Limits for Jupiter;" in this proceedings*

[3] *Kennel, C. F., and Petschek, H. E.; "Limit on Stably Trapped Particle Fluxes;" J. Geophys. Res.; Vol. 71; No. 1; pp. 1-28; 1966*

[4] *The figure has been changed to include both cases n=0.1 and n=1.0 and to express the results in omnidirectional fluxes as the other authors did.*

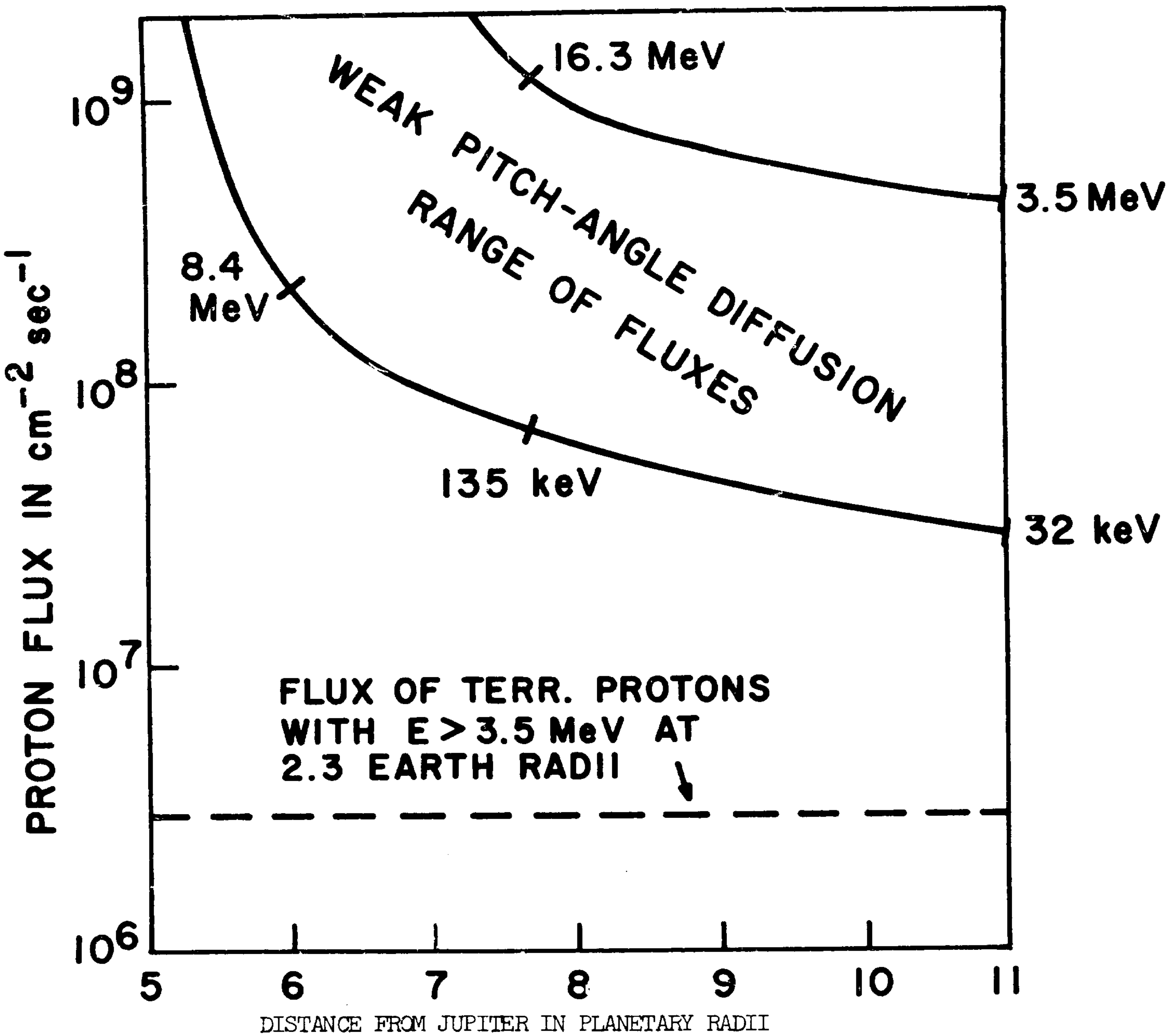

Figure 2. Proton Fluxes Near Jupiter

order of magnitude as the magnetic field energy density. It is shown in Figure 2, as the upper curve. Also shown are the minimum resonant energies contributing to the instability at a given L value.

I was looking then for a somewhat lower, I would say, characteristic flux--I wouldn't say upper limit--for the proton distribution by the following argument. I was considering the case where I have a particle source for the radiation belts which attains different values (from very low values to higher values). These increasing particle sources can, for example, be produced by increasing solar wind injection rates. At very low values of the particle source, there will also be an instability driven by the anisotropy; but this instability will not have the possibility to overcome the losses and will not contribute to the determination of the distribution function. This function in velocity space or momentum space will essentially be determined by other processes than momentum space diffusion. That is, for example, radial diffusion and the sweeping action of the satellites. These effects will create an anisotropy which is fairly large compared with the pitch-angle anisotropy caused by pure weak diffusion in momentum space in the region of consideration between L=5 and L=11. Close to the satellites, where the high-pitch angle particles just sneak through because of the tilt of the magnetic dipole, I estimated an anisotropy of about five. A conservative lower limit for the anisotropy for all distances was then estimated to correspond to n=1. Of course, when there is only radial diffusion from the outside, the anisotropy would probably be higher under the combined action of satellite-sweeping and radial diffusion.

On the other side of the argument, if diffusion goes outward, because there is some source inside, it would diminish the anisotropy. So, I essentially assumed n=1 for this calculation. The argument continues in the following way. When I further increase the particle source strength, the instability will just start to become self-sustained at a certain flux (the anisotropy of which is determined by processes other than momentum space diffusion). If I increase the source strength further, by a small amount or so, I will first come into a region, where the processes, which earlier determined the pitch-angle distribution, will compete with momentum space diffusion (until at some higher source strengths the weak pitch-angle diffusion case is reached essentially as the upper limit derived by Kennel and Petschek).

If one further increases the source strength by orders of magnitude, one can get the strong diffusion case. However, the strong diffusion case is ruled out for several reasons below about L=11. Some of them were given in these proceedings. Another reason is the following: It would, e.g., require very much energy for the radiation belt energy source to replace all the particles which are precipitating in the strong diffusion case, say, at densities which are interesting in the specific region inside L~10. If one assumes, for example, density values, which were discussed here and which correspond to one-tenth or so of the energy density of the magnetic field, one necessarily gets very large energy inputs from the radiation belt energy source in this region--the inputs of which are probably not reasonable. There could be, therefore, no steady strong diffusion inside about L~10. The only diffusion which could occur at all is weak diffusion. Now, my characteristic trapped flux just states that at a certain trapped particle flux, the anisotropy--and its spectral slope,are determined by processes other than momentum space diffusion; thus, the wave energy will start to become self-sustained. If I further increase the particle source of the radiation belts, it will become increasingly difficult to further increase the trapped flux, as it is essentially no upper limit but rather, a characteristic flux above which the continued augmentation of flux becomes increasingly difficult. What I then get is plotted as the lower solid curve and illustrated in Figure 2. For computation purposes, n=1.0 and m=3.0 were chosen.

If number densities had been used instead of flux, a peculiar minimum near L~6 would have been obtained. With flux on the ordinate, the minimum does not appear because of a strongly increasing lower limit for the energy integration. The resonant energy, from which we integrated upward, is again given by the energies noted on the curve and it goes up very strongly. Here we have 32 keV, 0.135 MeV and 8.4 MeV. It essentially confirms what has been said here today--that inside about L=5 or so, this mechanism doesn't play a role and has no practical application for this meeting. Above L~5, $\beta = 12 \times 10^{-3}$, 2.5×10^{-3}, and 4×10^{-3} at L=6, 8, and 11 respectively. I don't feel sure whether to call this an upper limit or not, but I would say that these are characteristic flux values above which it becomes more and more difficult to further increase the trapped flux.

DISCUSSION

DR. BRICE: I did not integrate from the characteristic energy up because if you conserve the first invariant, most of the particles may be at fluxes substantially above the characteristic energy. In that case, you are getting too large an answer if you integrate under the whole curve.

DR. NEUBAUER: Yes. You use somewhat higher energies[5].

DR. BRICE: If you have no particles at the low energies that are very near the limit, then your calculation will be an overestimate. I tried to take that into account. The other point is that this factor varies inversely as the anisotropy, and I used a slightly higher anisotropy than yours. That explains the discrepancy where you have $\beta \simeq 1$.

DR. NEUBAUER: I made this 0.1 to correspond to L=15. It gives a factor of 2 or so at L=5. It is a logarithm of one over the loss cone angle.

DR. BRICE: I am saying that you have $\beta \approx 1.0$, and I got $\beta \approx 0.1$. Our equations don't disagree, but we just disagree a little bit on the limits for the integrals and the anisotropy factors. I think $\beta = 0.1$ is perhaps a little more realistic.

DR. NEUBAUER: Let me take the energy, as you did, which gives a somewhat higher energy or so in the diffusion picture. You also have energies which go inward which are lower. I mean it is just a characteristic energy, isn't it?

DR. BRICE: Yes. But you may not have very many particles at lower energies--that's the point.

DR. NEUBAUER: I mean, what you are starting with, is a diffusion picture which is a distribution of energies or so.

[5]*Editorial Note: In the case of n=1.0, giving β around 10^{-2} between L=6 and L=11, the lower energy limits are smaller than the diffusion energies for L≥7 in Figure 2; in the case n=0.1, giving $\beta \sim 1.0$, they are larger, however.*

DR. BRICE: That's correct.

DR. KENNEL: I would like to report a discussion that Dr. Brice and I had over coffee. Let's take the point of view that the stably trapped limit does not affect particles directly for L<5, but can have a throttling effect as to how many get as far in as L=5. Because we only know about the electrons, it becomes of crucial importance to do the electron case relativistically with the appropriate energies and to compute the stably trapped limit with greater accuracy than we have done nonrelativistically in today's estimates. Now, if it should work out that we can get reasonable injection fluxes starting at L=5 to account for the somewhat lower synchrotron flux, then with Brice's help, we could fudge a diffusion coefficient and then the electron problem would be in fairly good shape. From there we would have a very accurate estimate of how many protons are actually there. So far as this research program is concerned, the whole question hangs on whether we can explain the electrons; if we can, we know the same is happening to protons.

DR. BRICE: That wouldn't change the limit we have established for the protons, but it would give us rather more confidence in the result.

DR. KENNEL: The limit would be the same, but the point is the electron fluxes are a bit too small, and if the relativistic corrections bring down the electron flux, then I think we would be in pretty good shape.

DR. BEARD: But aren't you estimating the electron fluxes on the decimetric emission?

DR. BRICE: What we are saying is that when we do the stability limit nonrelativistically for the electrons and the protons, we come up with an answer for the electrons that is about an order of magnitude too high to be in agreement with the decimetric radiation fluxes. Now, what we are suggesting is that if we do the electrons relativistically and do it correctly, that an order of magnitude discrepancy may disappear. If this happens, then we say that we have a very good explanation for where the decimetric electrons come from, and it is quantitative. That gives us considerable confidence in the physics that we have used and in applying the same to the protons.

DR. BEARD: I think this is excellent. But the only thing that I wanted to bring out was that the electrons are losing a lot of energy by synchrotron emission, and they hang around after they have emitted their synchrotron emission; therefore, you may be thinking in terms of too low an electron energy flux because you are ignoring the spent electrons. You are only thinking in terms of the electron fluxes responsible for the decimetric emission.

DR. BRICE: I don't think that is too serious a problem, because the onset of the decametric emission is going to be very rapid. I think if we take the peak value of the electron flux just before the decimetric onset, that that will be a very good estimate.

DR. BEARD: You mean just before the flux is reduced by the synchrotron radiation.

DR. BRICE: Yes. That estimate will be accurate.

DR. KENNEL: That is what we need from you, and what we need from the observers is a precise L-shell distribution, with resolution down to tenths in L.

DR. WARWICK: Dream on.

DR. BRICE: If we wait three or four years, Jupiter will be back where you can look at it.

DR. BEARD: I didn't realize you were thinking in terms of electron fluxes well beyond $2R_J$. If you are, then everything you said I agree with.

DR. NEUBAUER: I might just add something concerning the stability of the relativistic electrons. I did some calculations using the model by Clarke[5]. Of

[5] *Clarke, J. N.; "A Synchrotron Model for the Decimetric Radiation of Jupiter;" Radio Science; Vol. 5; p. 599; 1970.*

course, there is some uncertainty in this model (which is in all the models); it had essentially a large anisotropy at the inner belt and an anisotropy of three or so in the outer belt, which is what has been said here. At least this distribution function is stable with a fairly large margin.

DR. KENNEL: I think that is what we would expect. The crucial question is relativistic electrons at Io.

DR. BEARD: There is one other thing about the electron fluxes. Even at L=4, the only electrons we know about are the very energetic electrons, and you may have very much higher fluxes again, because you don't know anything about the electrons that don't radiate. There might be a broad tail. You could know it from the Faraday rotation but that sets only a much higher limit.

DR. WARWICK: Could I ask what the role of that Faraday limit in this (as we have talked about it) is?

DR. KENNEL: It is crucial in the sense that this instability operates to limit fluxes only above a certain characteristic energy. That characteristic energy scales as B^2 divided by the total electron density, so low densities force this instability to high energies where it is unimportant, presumably. High densities make it very important.

DR. WARWICK: So, may I direct our attention to the fact that there is a model dependence on Neil Brice's ionosphere diffusion problem which may be the weakest link in the chain. I don't want to stress that point. The decimetric flux is the sole datum that we have if you want to dismiss the Faraday effect. There are several orders of magnitude separation here.

DR. KENNEL: Unfortunately, your number is right where you can go either way.

DR. BRICE: If the densities don't increase once you go out above the ionosphere, then I think you really have to seriously reconsider the problem and think again. If for some reason the magnetosphere is not corotating so that the centrifugal force is not dominant out beyond about $2R_J$, the plasma densities will not increase above the minimum value. In that case, these stable trapping limits won't apply, but then the fluxes you would anticipate would be that much higher.

DR. SCARF: Again, there is an assumption here that when the electromagnetic ion-cyclotron instability occurs, you don't have a clear connection with density.

DR. BRICE: We must have enough cold plasma for the electrostatic cyclotron instability, but that requirement is much less stringent.

DR. THORNE: One also has to have at least one-tenth of the solar wind flux that gets across the boundary; in your model, this is quite reasonable because you don't have a boundary.

DR. CARR: Since the decametric Faraday effect is so important here, wouldn't it be worthwhile to do some new measurements and new analyses of old measurements to check that result?

DR. BRICE: I don't think that it is exceptionally important because the densities that we have are certainly adequate to introduce this flux limit and too, they also satisfy the decametric Faraday rotation requirement. If that requirement is inapplicable for some reason, then the allowable densities are much higher. In that case, we could have much higher cold plasma densities, but then much higher cold plasma densities are not going to influence these answers very much.

DR. KENNEL: The only thing that would influence the answer is if these densities got much lower.

DR. BRICE: If you have strong reasons to believe that the plasma densities are much lower, then it would be influential. So, we need a decametric measurement that is two orders of magnitude better than the one now available.

DR. WARWICK: The limit is set essentially by the total content of the terrestrial ionosphere.

DR. KENNEL: Is there any possibility of satellite observations?

DR. WARWICK: It could be done, but hasn't been.

DR. CARR: There is a very good possibility of a lunar station, which would be ideal.

DR. BRICE: You have to be looking at Jupiter when you are not looking at the sun.

DR. WARWICK: That is not a problem. The technique for doing it is clear enough. It just hasn't been proposed because I think that perhaps the importance of the limit has not been stressed until now.

DR. BRICE: I think we would have to say we would be very surprised if this limit were not violated at some point.

DR. KENNEL: There would be a throttle at some point, but I think it is worth pointing out that the estimates for the stably trapped flux are independent of density; the only requirement is that the density be high enough that the particles you are interested in resonate.

DR. BRICE: You are saying this is a threshold.

DR. CORONITI: If you take Brice's cold plasma density model at L=6 and do the *electrostatic* wave instability analysis of the cyclotron wave that Dr. Scarf has been talking about, the density is very critical because even a little cold plasma can drive those modes unstable, even for a rather small anisotropy. So, in conclusion, it is quite likely that we are missing the boat a little bit in thinking only about electromagnetic waves. The electrostatic waves could actually be the dominant process. We should compute those out, as well, to get a reasonable answer.

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AN ENERGETIC CHARGED PARTICLE EXPERIMENT ON THE ASTEROID/JUPITER MISSIONS PIONEERS F AND G

James A. Van Allen*

Introduction

The experiment for Pioneer F/G that was proposed originally in November, 1968 was comprised of detectors and circuits that had been used successfully over long periods of flight operations in Earth-orbiting (Injuns I, III, IV, and V; Explorers XII, XIV, XXXIII, and XXXIV; OGO's I, II, III, and IV), lunar-orbiting (Explorer XXXV), and interplanetary and planetary flyby (Mariners II, IV, and V) missions.

The general point-of-view as quoted from that proposal was, and continues to be, as follows:

"The writer is well aware of the tendency in space radiation work toward 'sophistication' in detector design. However, he continues to believe in the use of a diversity of simple, reliable detectors for exploratory work for several reasons:

"(1) Most of the principal discoveries and a large part of the detailed knowledge of energetic space radiations have come from the use of Geiger tubes, simple solid state detectors, and ionization chambers.

"(2) Several *different* detectors provide certain safeguards against 'being wiped out' by failure of a single element of the system.

"(3) A *diversity* of simple detectors with some redundancy provides a variety of checks on *internal consistency* and a number of different bases for analysis of the *nature* of

*Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa 52240

the radiation that is encountered in a new and complex situation.

"(4) The calibration of detectors is relatively straightforward to establish and the calibrations are stable.

"(5) Reliable and stable detectors and circuits have been devised over the years and proven in extended periods of space flight under realistic physical conditions.

"(6) Large dynamic ranges are available for coping with a wide diversity of situations.

"(7) The relative simplicity of the technology makes it feasible to have student participation at all levels of the work.

"(8) The detectors proposed herein are mechanically rugged, and are quite insensitive to radiation damage and to variations in operating temperature."

The originally proposed experiment comprised five detector assemblies, designated A, B, C, D, and E. In addition to systems of single Geiger tubes (A, B, and C) having various window thicknesses, proton energy thresholds E_p = 0.5, 2.0, and 2.3 MeV and electron energy thresholds E_e = 40 and 90 keV, there was a three-element linear coincidence telescope (E) having thresholds for double and triple coincidences $E_e \sim 2$ MeV, E_p = 10 MeV, and $E_e \sim 5$ MeV, E_p = 48 MeV. The further detector (D) was a single element, totally depleted silicon surface barrier detector having a thickness of 28 microns and four (nested) proton energy ranges. Such a detector has the special feature

$$0.2 < E_p < 50 \text{ MeV}$$
$$0.3 < E_p < 20 \text{ MeV}$$
$$0.5 < E_p < 4 \text{ MeV}$$
$$0.8 < E_p < 2 \text{ MeV}$$

that it is very insensitive to electrons of any energy. It was regarded as a vital feature of the experiment in that it would resolve the inevitable ambiguities in the responses of the Geiger tube detectors as it has done in a most valuable way in its many flight uses cited above.

However, the NASA Headquarters decision was to eliminate detectors A, B, C, and D and to accept only E for flight, despite the consequent reduction of only 1.0 pound and 0.35 watt.

Our negotiation to restore, at least, the solid state detector D to the package was unsuccessful and we were restricted to the use of Geiger tubes only.

In subsequent work we honored that restriction but have completely redesigned the experiment to use Geiger tubes only to the best advantage within weight and power specifications. Nonetheless, the loss of the solid state detector (with which we have had more flight experience than any other group) has substantially weakened our capability for *distinguishing* electrons from protons in mixed beams of unknown proportions and spectra. It is hoped that collaborative work with other energetic particle experimenters will help resolve some of the possible ambiguities.

Scientific Objectives

A. To make an exploratory survey of the absolute intensities, energy spectra, and angular distributions of energetic electrons and protons as a function of position along the encounter trajectory through the magnetosphere of Jupiter, giving emphasis to electrons in the energy range 50 keV $< E_e \lesssim 50$ MeV and to protons of energy $E_p > 5$ MeV.

B. To use the foregoing observational data (1) to improve basic understanding of the origin and generalized nature of planetary radiation belts; (2) to provide a quantitative basis for interpreting the decimetric (and possibly the dekametric radio emissions of the Jovian magnetosphere; (3) to provide certain parametric limits on the magnitude, orientation, and eccentricity of the magnetic moment of the planet; and (4) to establish the radiation environment of Jupiter as an engineering constraint on future flyby orbiting, and landing missions.

C. To study the occurrence, intensity, and angular distribution of solar electrons $E_e \gtrsim 50$ keV and their propagation through the interplanetary medium to large heliocentric radial distances.

D. To use data on the angular distribution of solar electrons to infer the direction of the interplanetary magnetic vector.

E. To measure the heliocentric radial gradient of the sum of the intensities of solar and galactic cosmic ray protons $E_p > 70$ MeV.

F. To study the occurrence, intensity, and angular distribution of solar protons $E_p > 5$ MeV and their propagation through the interplanetary medium to large heliocentric radial distances.

Gross Instrumental Characteristics

A. Weight: 3.6 pounds

B. Power: 0.80 watt

C. Uses Geiger-Mueller (GM) tubes only as basic sensors

D. Telemetry: 12 bits (= 4 words) in each 192-bit main science frame (MSF) (i.e., 6.25% of science telemetry) in basic format. Quasi-logarithmic data compression is used in all channels to maintain 1% accuracy at all possible counting rates.

E. Operational: The experiment is designed to operate continuously in a single basic mode throughout flight, including Jovian encounter. A completely redundant logic package is provided internal to the experiment. Command switching from "main" to "standby" processor is the only mode change provided, other than the "power on"/"power off" command.

F. Angular Distributions: Angular distributions of the counting rates of all data channels can be accomplished by software procedures in the data analysis, using the S/C roll index and ambient roll rate, as follows:

(1) Good angular resolution at S/C bit rates of 2048, 1024, 512, 256, and 128 bps

(2) Useful but coarse resolution at 64 bps

(3) Very coarse resolution at 32 bps

(4) No resolution at 16 bps

G. Duty Cycle: Accumulation of counts from the eight data channels is on a duty cycle of 9.09% for six channels and 18.18% for the other two.

H. Physical Configuration of Package: The entire experiment is housed in a single package which (excluding protruding connectors) can be contained within a rectangular parallelepiped, whose outboard face has a Y-dimension of 6.75" and a Z-dimension of 5.70"; the X-dimension is 5.69". A hood projects outward through the side wall of the spacecraft and the thermal blanket to provide open fields of view for detectors A, B, and G. The above X-dimension includes the outermost portion of this hood (Figure 1).

Detectors

A. The University of Iowa experiment utilizes four EON 6213 GM tubes and three EON 5107 GM tubes as elementary detectors. The 6213 is a mica end-window (1.3 mg cm^{-2}) tube having a cylindrical volume of detecting gas 0.6 cm in length and 0.24 cm in diameter (Figure 2); the 5107 is a miniature cylindrical tube having a stainless-steel wall 30 mg cm^{-2} in thickness and a cylindrical volume of detecting gas 0.8 cm in length and 0.15 cm in diameter (Figure 3).

B. Three of the 6213's (designated A, B, and C) are arranged in an array to serve as a multi-function particle telescope (*Geiger-Mueller Tube Telescope, GTT*) (Figure 4). The axes of the three tubes are parallel to each other and to the X-Y plane of the spacecraft. The tubes are stacked one-above-the-other in the order B, C, A to form a telescope

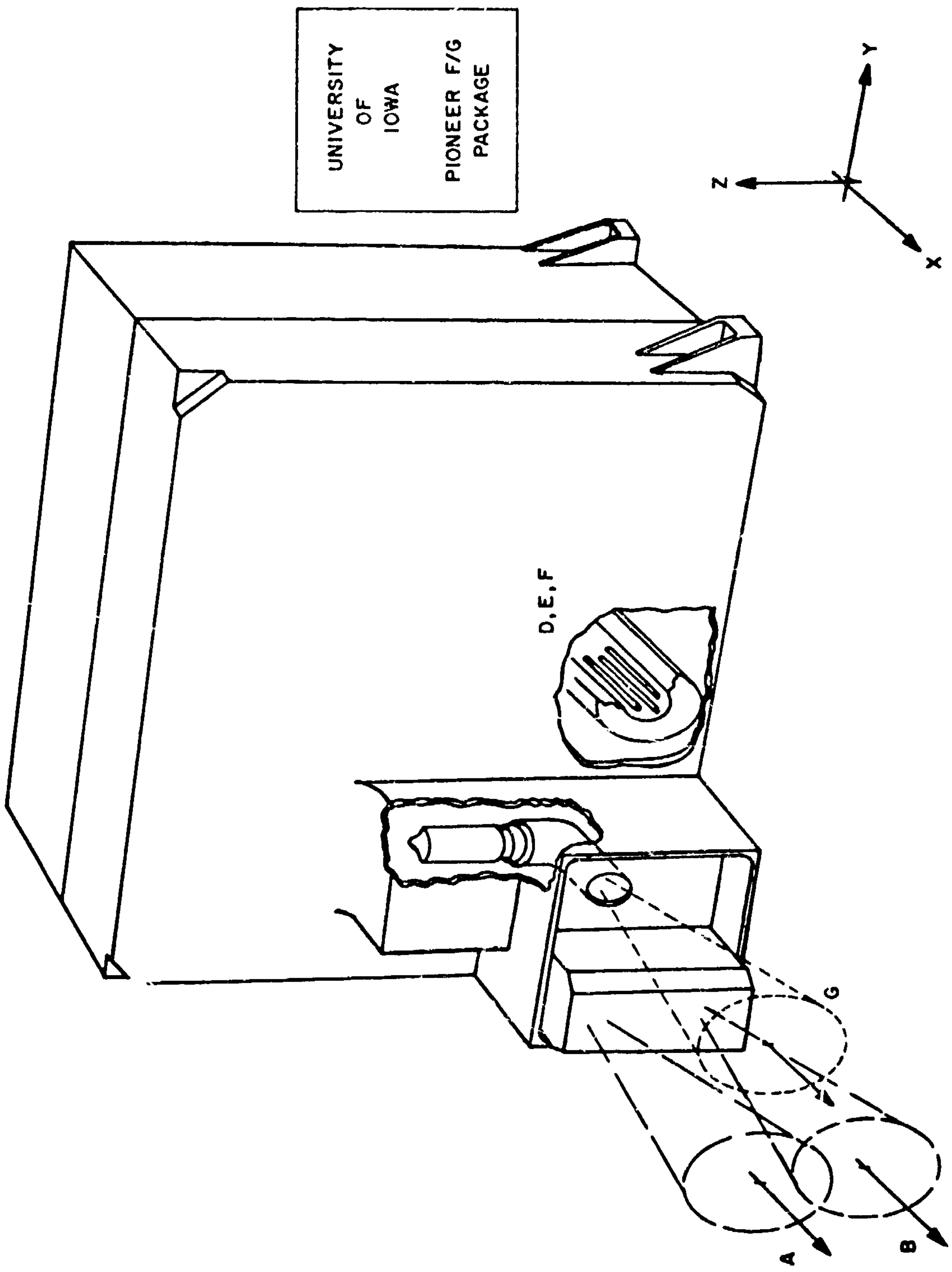


Figure 1. University of Iowa Experiment Package Configuration (Excluding Ex[illegible]nal Connectors)

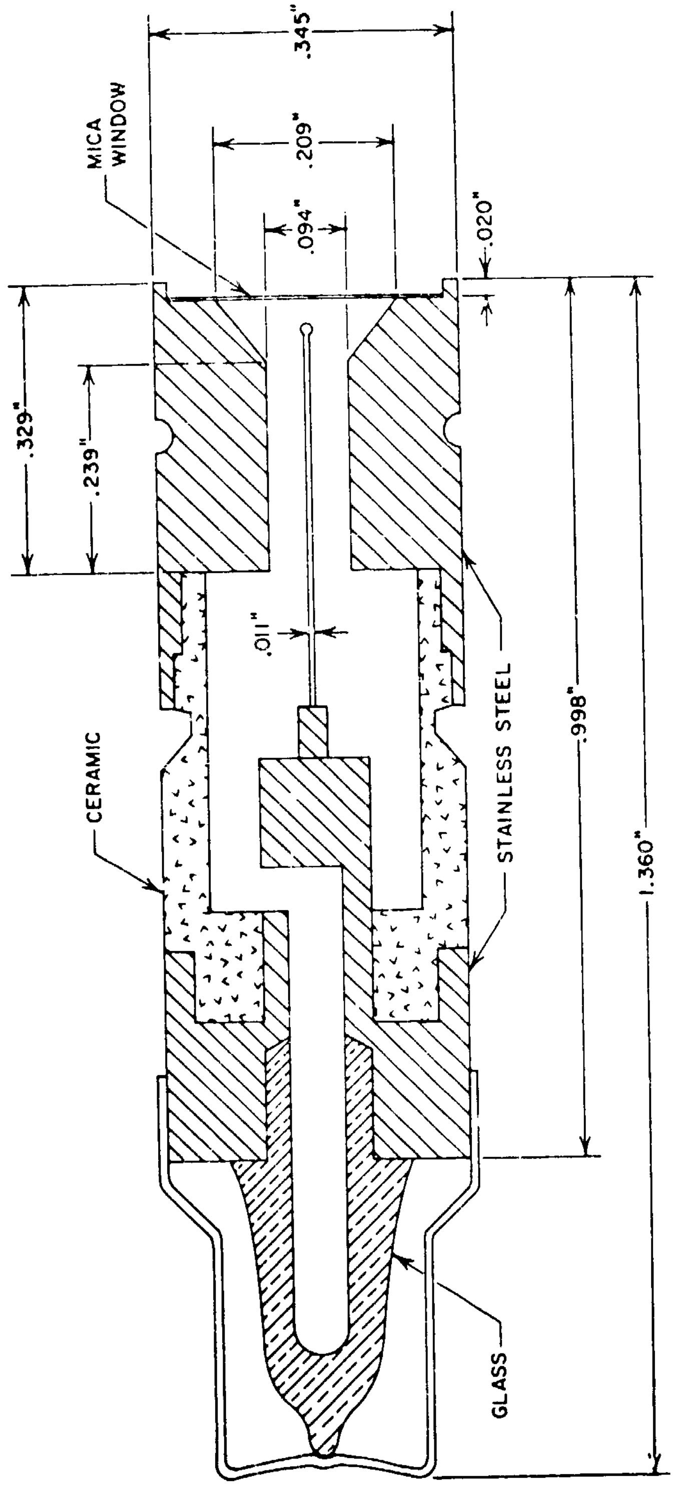


Figure 2. Section of EON 6213 GM Tube with Mica End-window

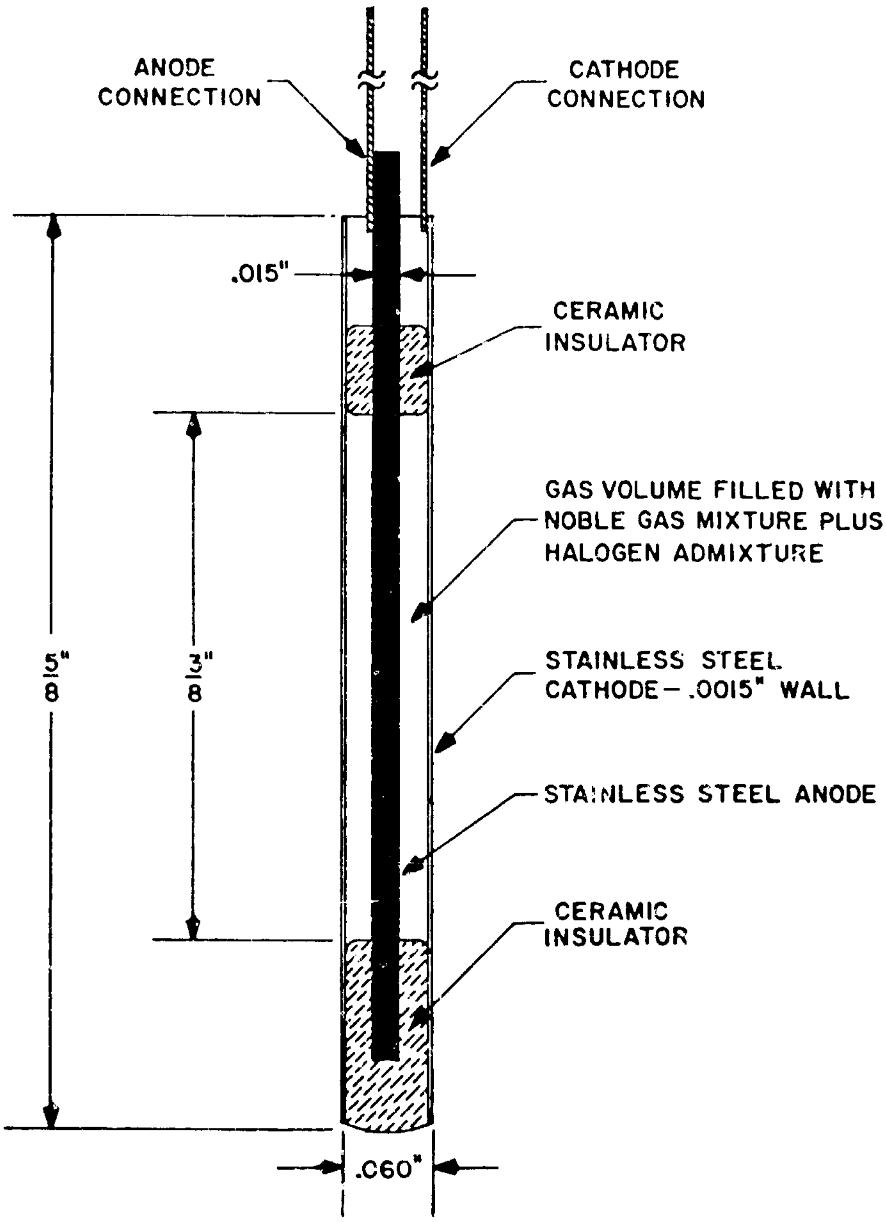


Figure 3. Section of EON Type 5107 Geiger-Mueller Tube

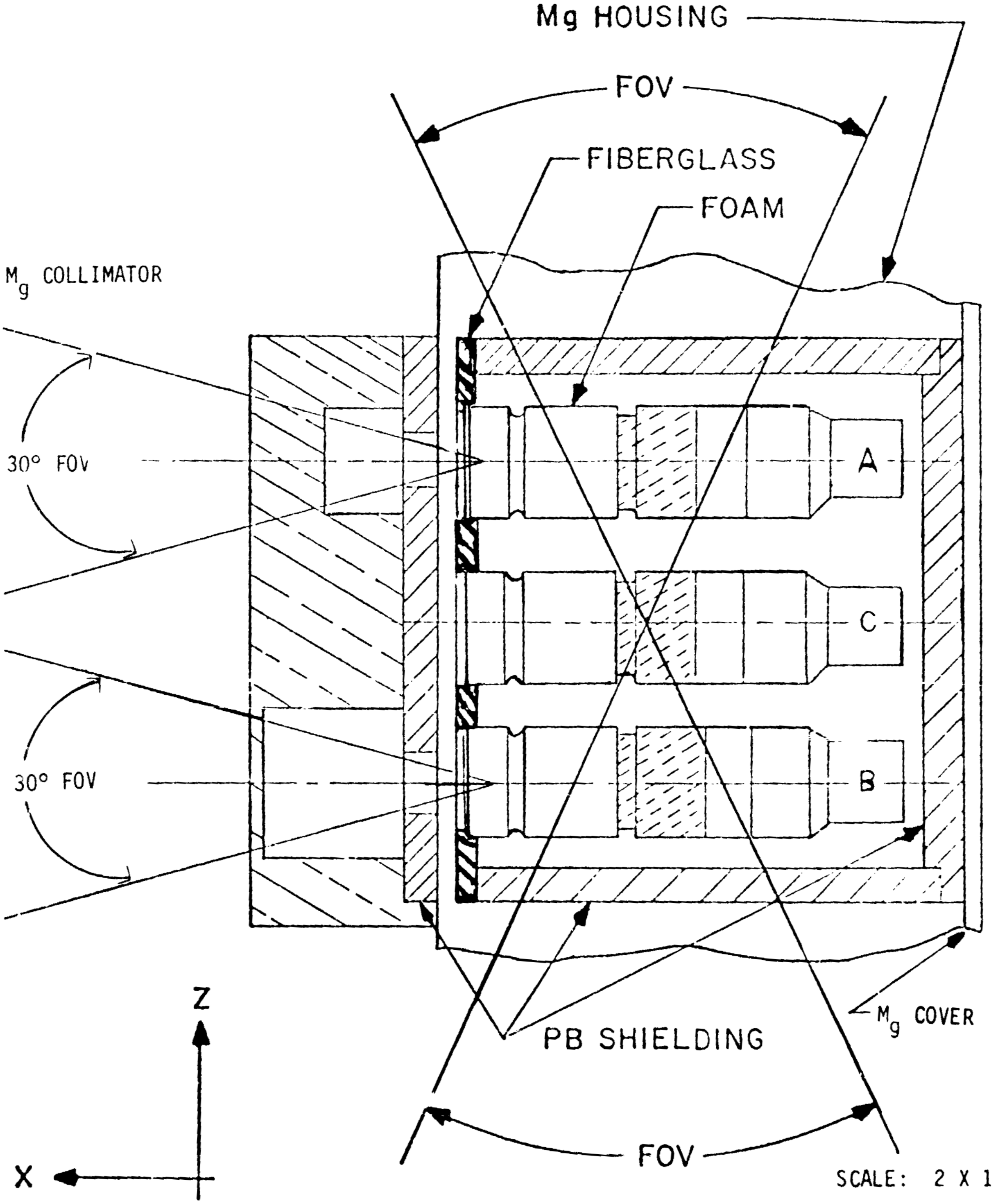


Figure 4. Geiger-Mueller Tube Telescope Assembly (Section)

for penetrating particles (E_p > 130 MeV) moving approximately in *either the +Z or -Z direction*. Coincidences ABC and AB are formed with a resolving time of 1.0 microsecond. In an idealized instrument, the rate of ABC is equal to the rate of AB. The departures from this situation provide information on the efficiency of the intermediate tube C and the effects of accidental coincidences. The separation of the axes of the two outside tubes A and B is 2.62 cm, the nominal bidirectional geometric factor is 4.3 x 10^{-3} cm^2 sr, and hence galactic cosmic ray rates of ≈ 1.2 x 10^{-2} sec^{-1} for ABC and AB are expected. At the intended accumulation duty cycle of 18.2% for ABC and 9.1% for AB, there are expected about 190 galactic cosmic ray counts in ABC and 95 in AB per day of continuous data.

The windows of A, B, and C face outwards from the body of the spacecraft in the +X direction with the axes of the tubes parallel to the X-axis. Tube A is provided with a 30° full vertex angle collimator and a magnesium shield of 1.10 g cm^{-2} (E_e > 1.9 MeV, E_p > 30 MeV). Tube C is "completely" shielded by 2.21 g cm^{-2} of magnesium plus 3.60 g cm^{-2} of lead (E_e > 10 MeV, E_p > 73 MeV). Tube B is also provided with a 30° full vertex angle collimator and has a magnesium shield of 0.058 g cm^{-2} (E_e > 0.22 MeV, E_p > 5.4 MeV). As the spacecraft rotates around the Z axis, the two directional tubes A and B scan an equatorial strip of the unit sphere within ± 15° of the X-Y plane of the spacecraft. Their individual counting rates will be used to determine the angular distribution within this strip. Detector C provides the pertinent background rate (caused by penetrating radiation) for A and B. The nominal unidirectional geometric factors of A and B are 1.5 x 10^{-2} cm^2 sr and the accumulation duty cycle for each of the three individual tubes A, B, and C is 9.1%.

The entire GTT except for the apertures of A and B is shielded by 3.6 g cm^{-2} of lead plux 0.5 g cm^{-2} of magnesium plus incidental package and spacecraft shielding. The detection characteristics of the GTT are summarized in Figure 5 (2 pp.) Two sample calibration curves of the apparent counting rate r vs the true counting rate R for single detectors A and B of the prototype unit

A: $g = 1.5 \times 10^{-2}\ cm^2$ sterad

Conical collimator: 30° full angle (along +X axis)

$E_e > 1.9$ MeV

$E_p > 30$ MeV

Dynamic Range: Bkg to 10^7 counts/sec

Angular distributions

B: $g = 1.5 \times 10^{-2}\ cm^2$ sterad

Conical collimator: 30° full angle (along +X axis)

$E_e > 0.2$ MeV

$E_p > 5.4$ MeV

Dynamic Range: Bkg to 10^7 counts/sec

Angular distributions

Figure 5. University of Iowa Geiger Tube Telescope (GTT)
(Sheet 1 of 2)

C: Shielded monitor for A and B

Non-directional

Dynamic range: Bkg to 10^7 counts/sec

ACB, AB: Coincidence telescopes along Z axis

$g = 4.3 \times 10^{-3}\ cm^2\ sterad$

$E_p > 130$ MeV

$$\frac{ACB}{AB} = \epsilon, \text{ efficiency of C}$$

Figure 5. University of Iowa Geiger Tube Telescope (GTT)
(Sheet 2 of 2)

are given in Figures 6 and 7. These curves have been extended to $R \sim 10^8$ counts/sec using a 5000 curie Co^{60} source.

C. The three 5107's (designated D, E, and F) are arranged with their axes parallel in a symmetrical triangular array to form the *Geiger-Mueller Tube Shower Array* (GSA) (Figure 8). The spacing of the tubes is such that no straight line can pass through all three tubes. Hence, the triple coincidence rate DEF (1.0 microsecond resolving time) is ideally a measure of the number of multiple-particle events or showers. In practice, there will also be contributions by accidental coincidence. Since the three tubes share an identical physical environment, the single counting rate of only one (D) is transmitted to provide a basis for the estimation of the rate of accidental coincidences. The triangular array of 5107's is shielded on all sides by 7.2 g cm^{-2} of lead plus incidental package and spacecraft material. The "critical energy" for electrons in lead is 9.5 MeV. An electron of this energy in lead loses energy by ionization and by radiation at an equal rate. At greater energy, radiation loss and hence electron-positron shower production dominates. The adopted shield has a thickness greater than the radiation length 5.9 g cm^{-2}. The radiation length is defined such that in a thickness of 5.9 g cm^{-2}, an electron of energy much greater than the critical energy loses $1 - e^{-1} = 63\%$ of its energy by radiation. The results of a preliminary experimental calibration of the response of the GSA to electrons in the energy range 10 to 40 MeV are shown in Figures 9 and 10. These calibrations demonstrate the fulfillment of the design objective (Figure 11) of having a detector that is uniquely sensitive to electrons $E_e \gtrsim 20$ MeV, provided the single rates of D, E, and F do not exceed $\approx 10{,}000$/sec. The array has not yet been tested with high energy protons but the DEF/D ratio is expected to be less than 10^{-4} for protons $E_p < 200$ MeV.

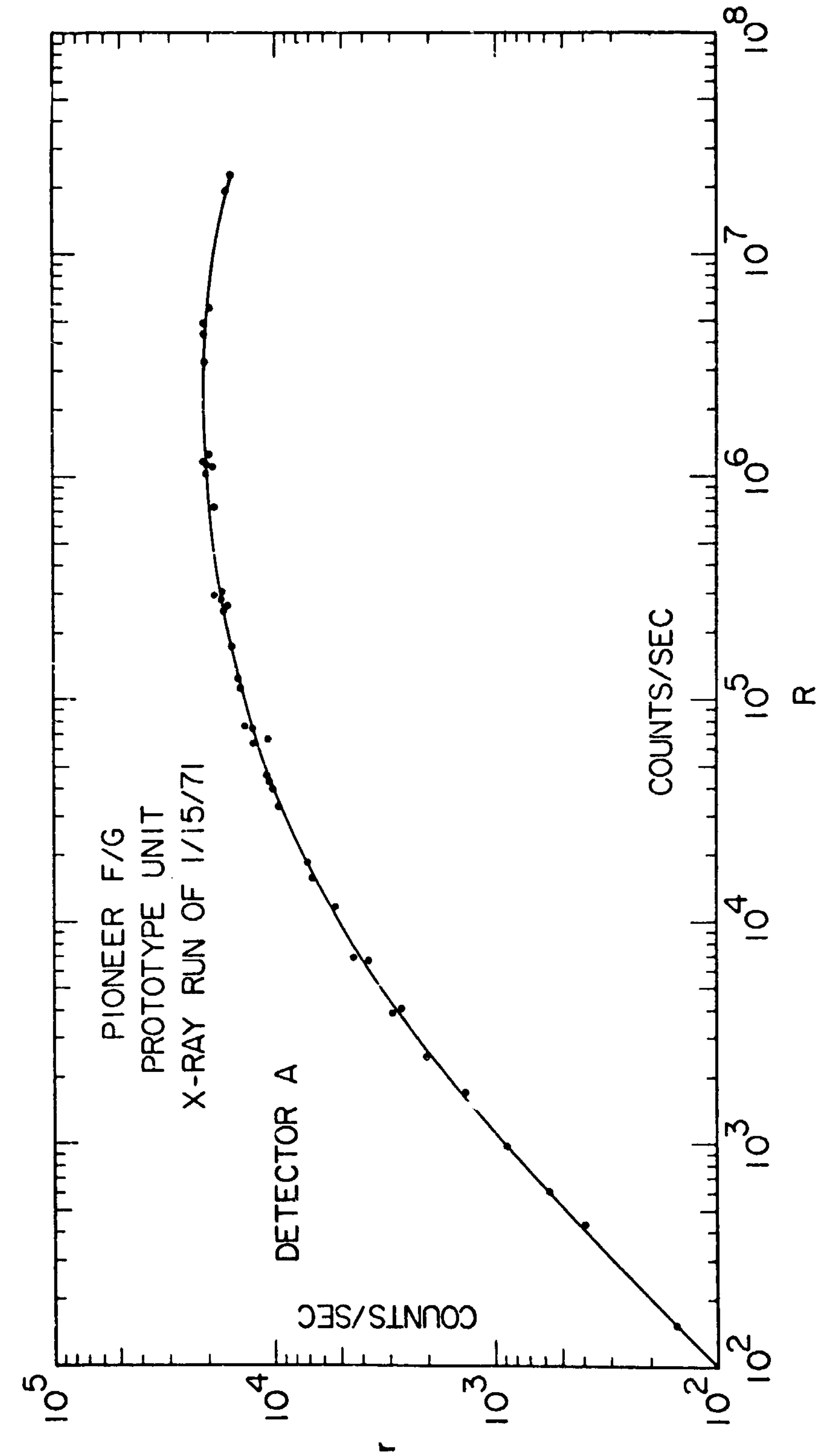


Figure 6. Sample Calibration Curge for Detector A

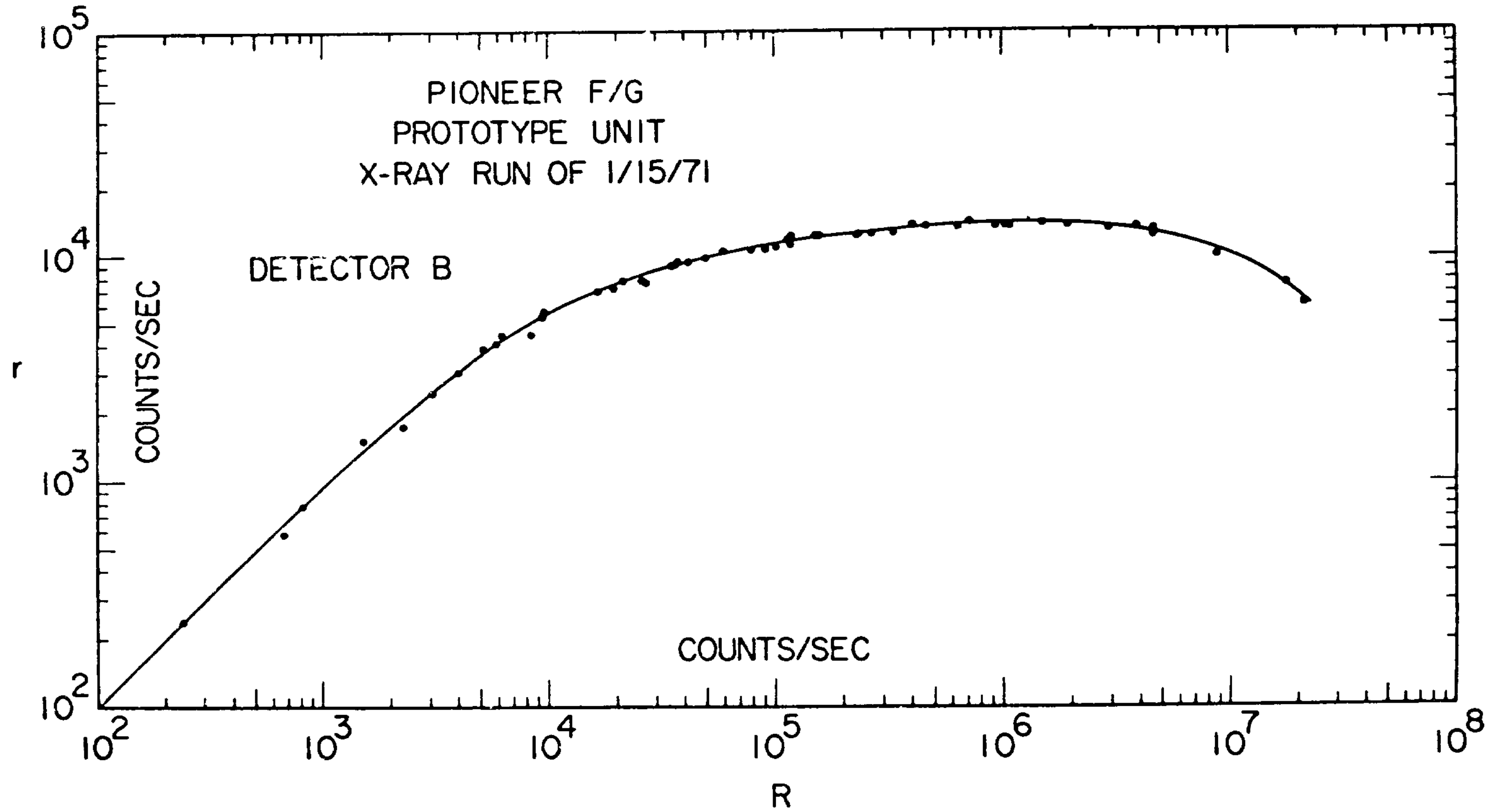


Figure 7. Sample Calibration Curve for Detector B

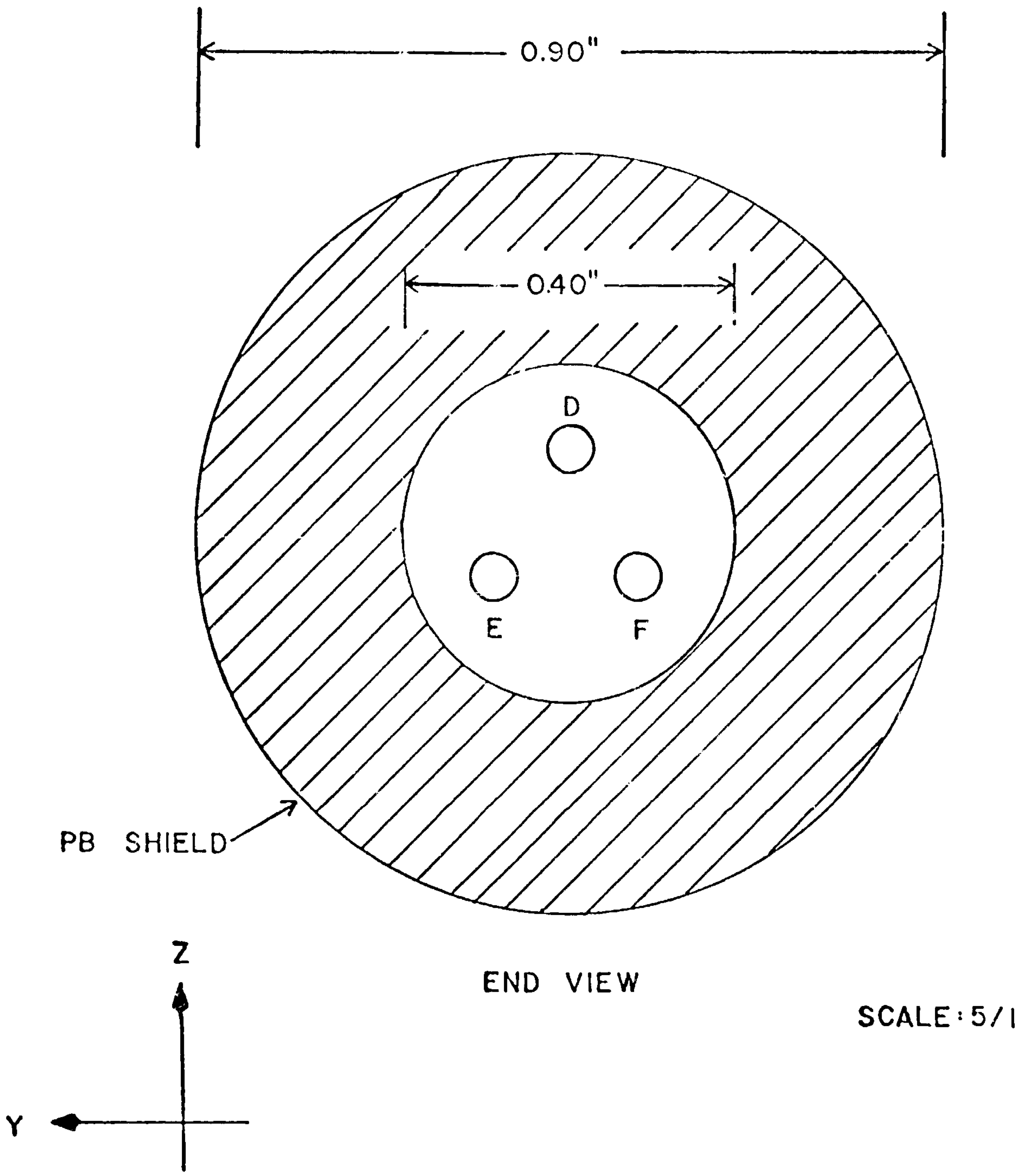


Figure 8. Geiger-Mueller Tube Shower Array (GSA)

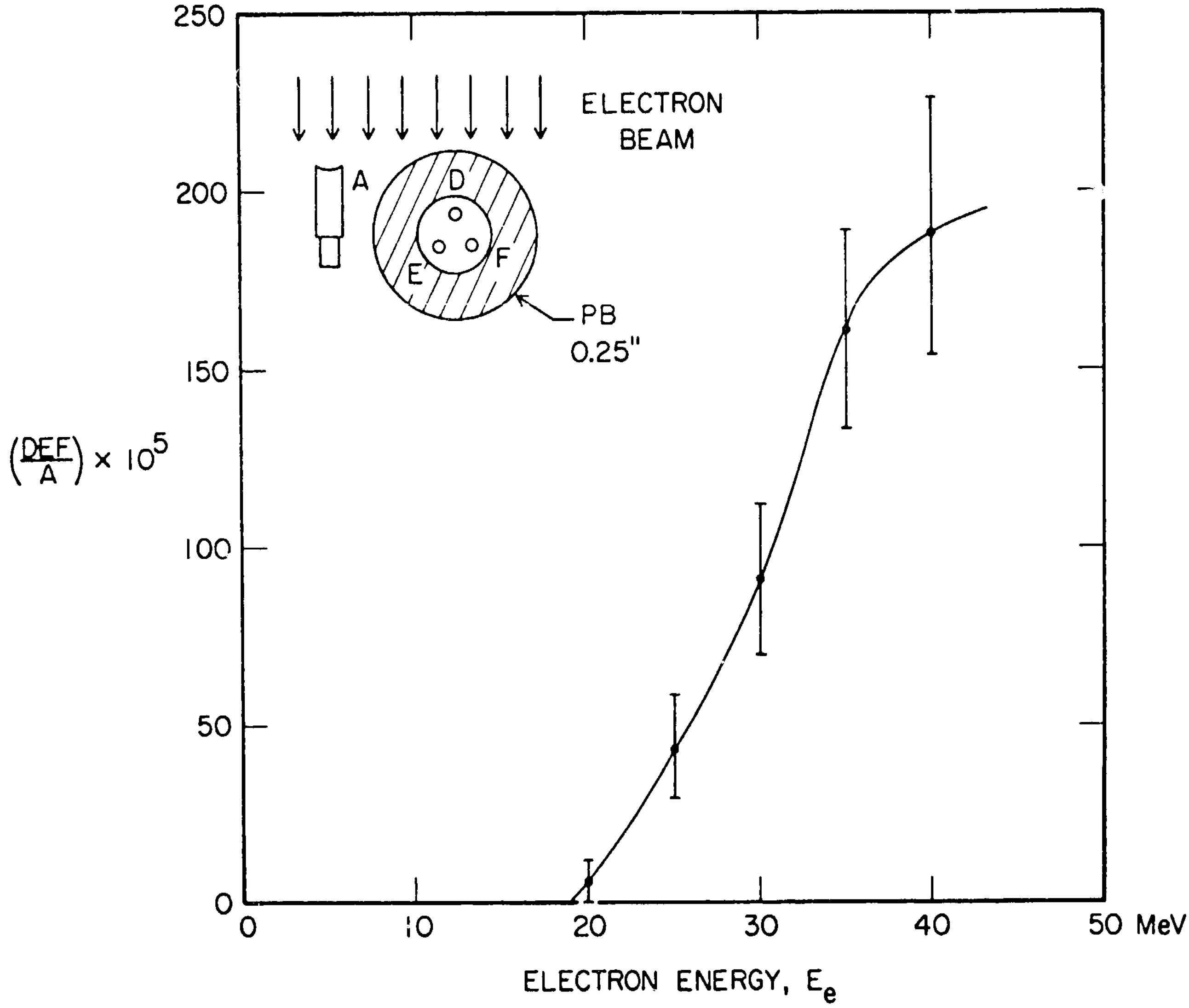


Figure 9. Calibration Response of GSA to Electrons, Result A

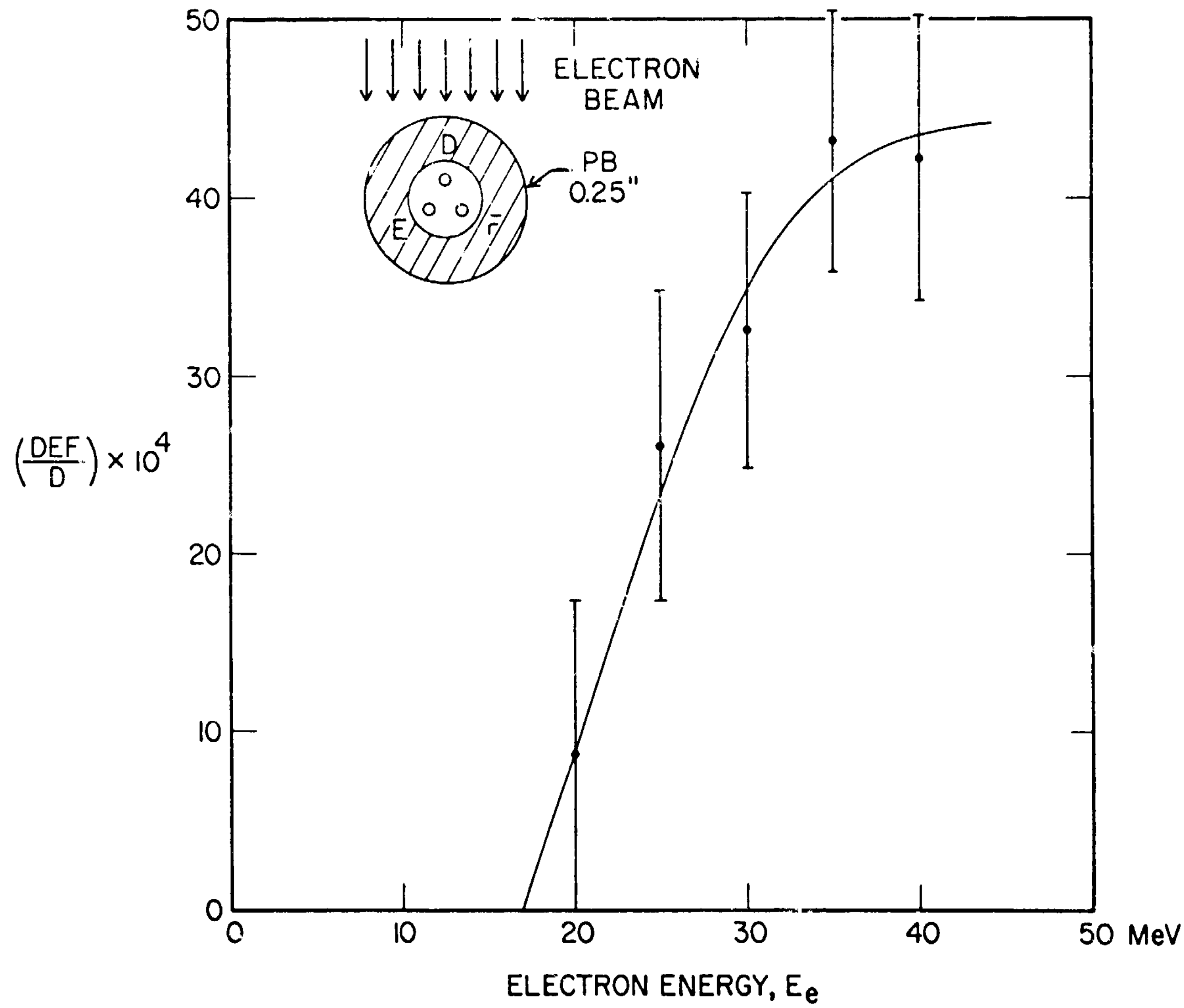


Figure 10. Calibration Response of GSA to Electrons, Result B

D,E,F: Shield: 7.3 g/cm^2 of lead

(1.24 radiation lengths)

$E_p > 65$ MeV

Single tube dynamic range: Bkg to 10^7 counts/sec

DEF: Triple coincidence triangular array

$E_e > 10$ MeV

Efficiency an increasing function of electron energy

(to be determined experimentally)

Insensitive to protons of any energy

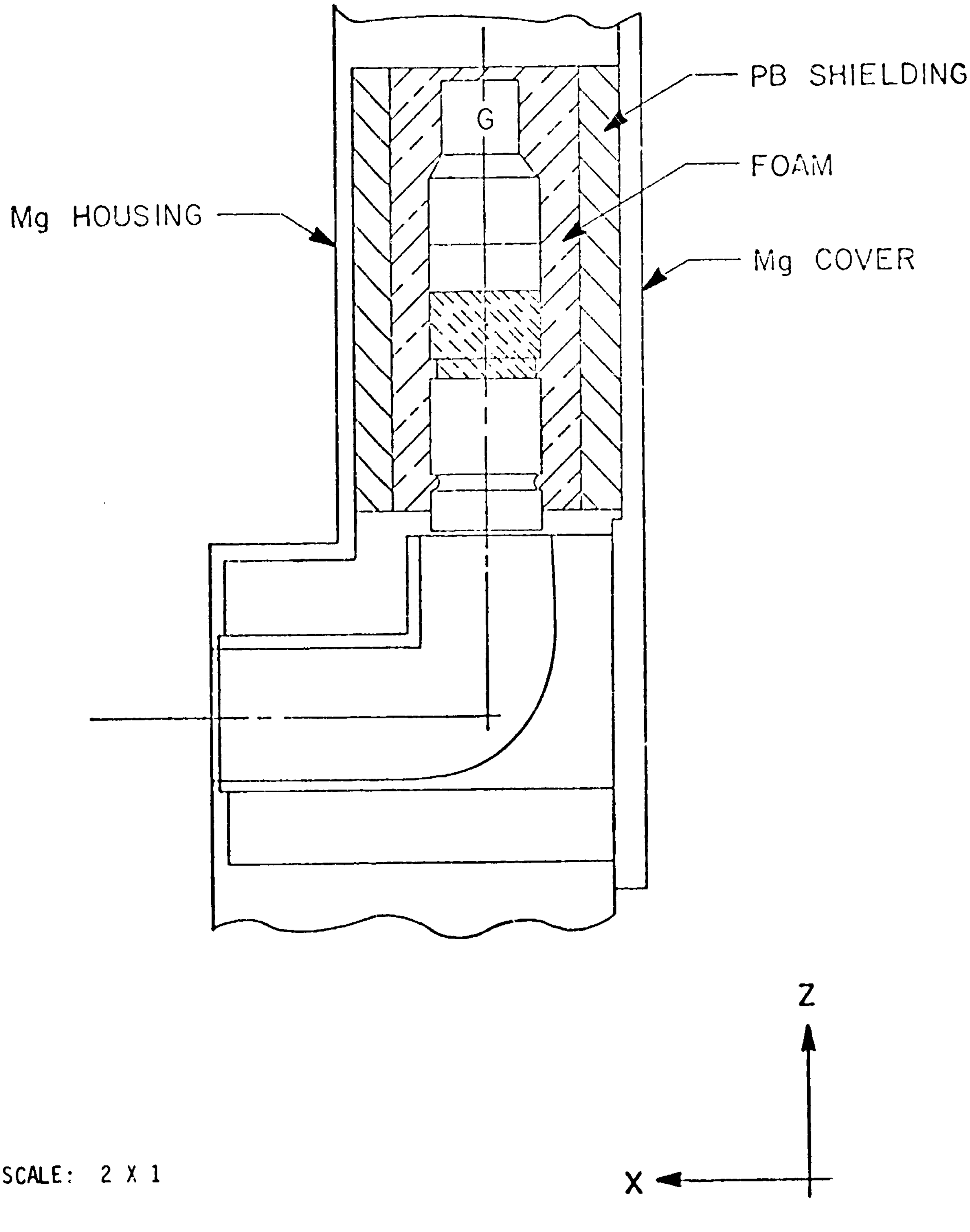
Figure 11. Parameters of the Geiger-Tube Shower Array (GSA)

D. One 6213 tube (designated G) is arranged in "scatter geometry" to measure electrons $E_e > 50$ keV in interplanetary space and in the outer fringes of the Jovian magnetosphere, including the shock front and the magnetotail. It is insensitive to protons $E_p < 60$ MeV. This is called the *Low Energy Electron Detector, LED* (Figure 12). The collimator is conical with a nominal full vertex angle 45°, looking outward from the spacecraft in the +X-direction. The effective unidirectional geometric factor is about 1×10^{-3} cm^2 sr (Figure 13). The angular distribution of particles within $\pm$ 22° of the X-Y plane of the spacecraft will be measured as the spacecraft rotates. The scattering efficiency and actual geometric factor have been determined experimentally. The accumulation duty cycle of G is 18.2%. In Figure 14 are shown calibration curves of the angular response of the LED for C^{14} electrons.

General Remarks on Capabilities of the Experiment in the Jovian Magnetosphere

A. On the approach to Jupiter, the first indication of the presence of its magnetosphere will, presumably, be by the low energy electron detector G and possibly B, as the S/C crosses the shock front and magnetopause on the sunward side of the planet. These detectors will also, presumably, be the ones to see the last vestige of the magnetosphere as the S/C recedes from the planet after encounter. The scatter geometry of G (in combination with the rate of B) will provide a distinction between protons and electrons and may permit a separate determination of protons and electron intensities in the energy ranges previously given.

B. Within the radiation belts of Jupiter, the GSA will conclusively identify electrons $E_e \gtrsim 20$ MeV and measure their omnidirectional intensities, provided the single rates D, E, and F do not exceed $\approx$10,000/sec. At higher single rates,



SCALE: 2 X 1

Figure 12. Low Energy Electron Detector (LED)

G: $g^* \approx 1 \times 10^{-3}$ cm^2 sterad (scatter geometry)

Conical collimator: 45° full angle (along +X axis)

$E_e > 0.050$ MeV

Insensitive to protons of $E_p < 60$ MeV

Dynamic range: Bkg to 10^7 counts/sec

Angular distributions

Figure 13. Parameters of the Low Energy Electron Detector (LED)

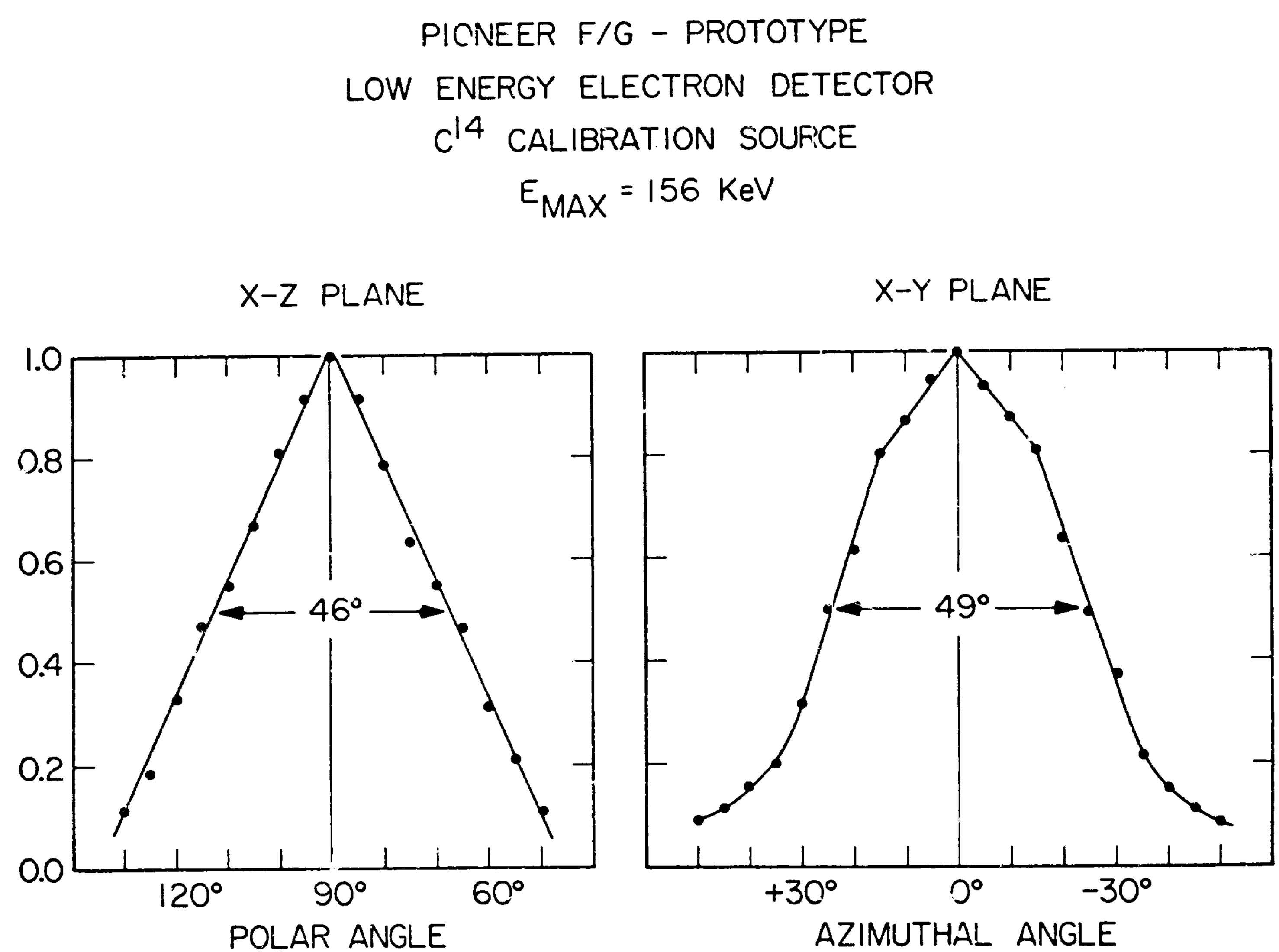


Figure 14. Angular Response Calibration Curves for the Low Energy Detector (LED)

the efficiency of triple coincidences is much degraded by dead-time.

C. In the absence of protons, $E_p \gtrsim 5$ MeV, the combination of detectors G, B, A, and DEF will provide a crude, absolute spectrum of electrons over the energy range 50 keV to 50 MeV and over a large dynamic range (at least to $10^8/cm^2$ sec sr above 50 keV).

D. Protons of $E_p \gtrsim 5$ MeV can considerably bewilder the determination of the electron spectrum, but it may be noted that only those protons having energies greater than $E_p \sim 70$ MeV can affect C, G, D, E, or F. Hence, even in this case, there remains substantial diagnostic capability. In the lower energy ranges, $E_p \sim 10$ MeV, the insensitivity of G to protons will again help resolve protons from electrons in their composite contributions to the rates of A and B.

E. Throughout the analysis of the encounter data, full use will be made of all observed dependences of counting rates on position along the trajectory, on angular distributions, and on the presumed diurnal "wobble" of the Jovian magnetosphere to improve the resolution of species and other observational ambiguities.

F. By calculation and by physical calibration, a family of "unit response" functions is being developed for the full array of detectors. Each element of the system is, however, a nonlinear one and not all elements are independent. Hence, only at low counting rates will the interpretation of observations be elementary.

DISCUSSION

DR. BRICE: One comment I might make, and that is I think the theorists among us would agree that in order to evaluate the maximum proton flux, that we don't have to go all the way into 1-1/2 Jupiter radii. If the window occurs out at 5 or 6 Jupiter radii, if we get some reasonable measurement into 4 or 3 Jupiter radii, we should be able to extrapolate in from there. So, the question I have is whether we can get enough information from your detectors or the other detectors to answer that question of what the fluxes are and what diffusion mechanisms are operative and what limits there are on the fluxes.

DR. VAN ALLEN: Right. Well, I think everyone in the experimental game is very sensitive to making everything you can out of the approach and recession part of the trajectories, and it may well be that we will go out of business in the immediate vicinity of the planet. That is quite possible.

DR. BRICE: What I am saying is it would be very nice if we could fly by at 3 or 3-1/2 Jupiter radii where the spacecraft is likely to survive and still get a handle on what things are like down to 1-1/2 or 2 so that we know how close in we can go next time.

DR. VAN ALLEN: We have sort of opted for this close of a pass--sort of a drop-dead trajectory--as we want to go right in. And, of course, we covered all radial distances from infinity to 2-1/2, so we do get a, so to speak, radial cut.

Now, in addition to that, as you know, if the magnetic axis is in fact wobbling back and forth and if the spacecraft were in the equatorial plane of the rotational axis, since this is about an 11-hour period and, as I mentioned before, the total encounter within 50 R_J is about 120 hours, there are several cycles of rotation that occur, even when we are within much closer radii than that.

If you use th- magnetic moment vector as the reference direction, then the spacecraft has some very complicated wiggles. If this were the equatorial plane, we could cross in and out and so on. It is a very important experimental thing to have this feature so that you wobble a number of parameters and see how things change as a function of those parameters.

That is in addition to the basic radial dependence and in addition to the angular dependence. So, at least in our experiment, we have what we call the low intensity regime where we are in good shape and can measure things definitively. In the high intensity regime, all the counters become nonlinear and interdependent.

We are in the business of constructing what I call unit response functions for all the detectors, and that is fairly simple to do, both experimentally and by calculation, but the problem is, like, the ABC coincidences are influenced by the individual rates, so everything becomes nonlinear and more or less interdependent. So it is possibly a completely bewildering undertaking to sort this out cleanly and uniquely when we get to high intensities, and I think that is a statement that would apply to all the detectors, because, as you know, any kind of a detector is sensitive to everything--neutrons, gamma rays. It is a question of intensity.

DR. KENNEL: How many separate flux measurements do you get in crossing the orbit of the satellite Io near L=6? It is about 8,000 kilometers across, isn't it? And the satellite's speed is 50 kilometers a second, right?

DR. MEAD: Diameter is about 3,500 km.

DR. VAN ALLEN: 30 km/sec is about the linear velocity of the spacecraft. That is 100 seconds. Well, we are in pretty good shape. Depending on the bit rate that turns out to be feasible, we will get about a measurement every second.

DR. KENNEL: So you *could* get radial profiles.

DR. BRICE: What is the spin rate?

DR. VAN ALLEN: 5 RPM is the spin rate or the spin period is 12 seconds.

ASSESSMENT OF JUPITER'S TRAPPED RADIATION BY PIONEER

John D. Mihalov*

INTRODUCTION

The primary objectives of the Pioneer F/G missions are to conduct exploratory investigations beyond Mars' orbit, during the favorable launch times of 1972 and 1973, of the interplanetary medium, the nature of the asteroid belt and the characteristics of Jupiter's atmosphere and magnetosphere. The Pioneer F launch is scheduled for February 28 to March 11, 1972, and encounter with Jupiter nominally will take place ~650 days later. The near-equatorial flyby past Jupiter is planned for distances near a jovicentric range of 2.5 to 3 planetary radii (R_J). For a 3 R_J jovicentric distance of closest approach, Pioneer F will be closer than 15 R_J to the planet for 28 hours, or during 2.8 rotations of the planetary magnetic field with respect to a heliocentric coordinate system. The Pioneer G launch date is about 13 months after that of Pioneer F, and the trajectory near Jupiter is to be planned late this summer.

The ~565-lb Pioneer F/G spacecraft are spin-stabilized, with the spin axis directed toward Earth so that Earth will be illuminated by a high-gain antenna. The basic spacecraft structure is made up of two thermally controlled equipment compartments mounted on the back of the 9-foot diameter reflector of the high-gain antenna. The high-gain antenna feed and, in the deployed condition, four radioisotope thermoelectric generators (RTG) and the magnetometer sensor are located on extensions from the basic structure. Figure 1 is a line drawing of the spacecraft exterior with the four energetic particle experiment packages shaded. Figure 2 shows the components within the two equipment compartments, again with energetic particle experiment packages emphasized. The spacecraft spin rate is to be near 5 rpm. The expected data transmission rate from Jupiter is 1024 bps, using the 210-foot diameter antennas of the Deep Space Network. This gives one complete main frame of data in 3/16 sec. The

*Ames Research Center, NASA, Moffett Field, California 94035

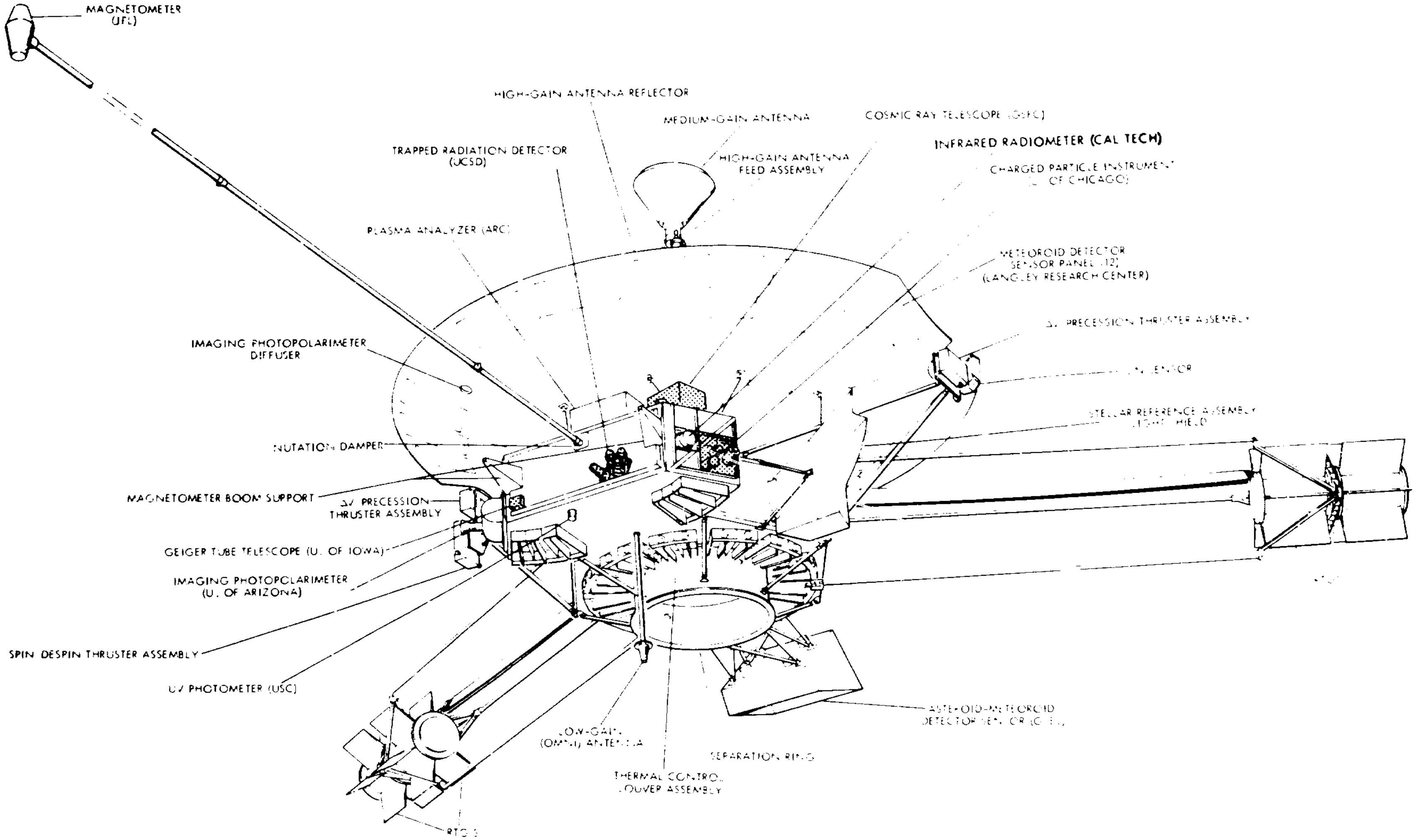


Figure 1. Pioneer F/G Spacecraft

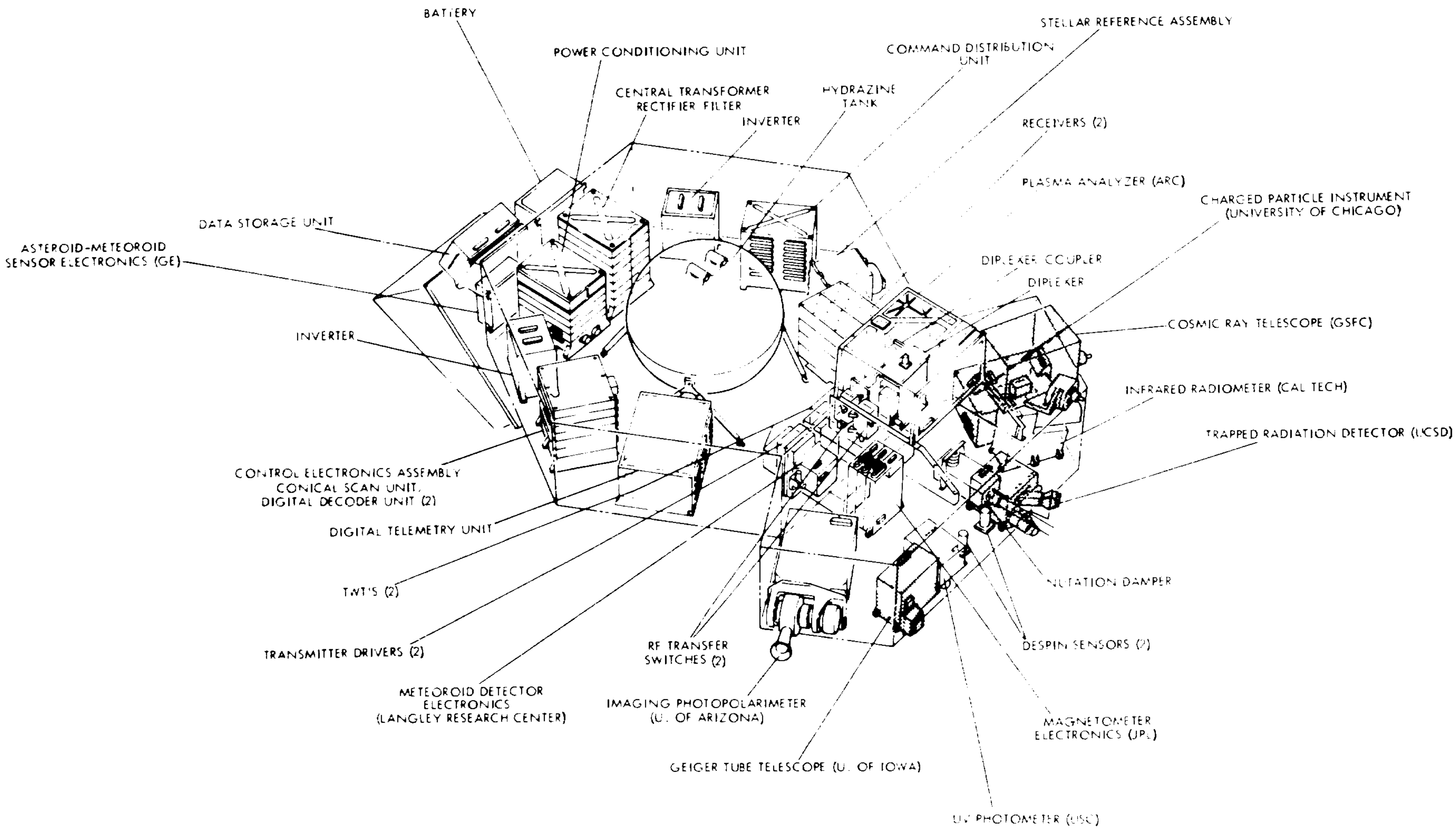


Figure 2. Components Within the Two Equipment Compartments of the Pioneer F/G Spacecraft

spacecraft data system permits bit rates every factor of 2 from 16 to 2048 bps. Special precautions are employed to minimize the residual and induced spacecraft magnetic fields to a value with magnitude less than 0.1 gamma at the magnetometer sensor location on the end of a 20-foot boom.

The Pioneer F/G experiment complement includes four energetic charged particle experiments, one of which is entirely devoted to Jupiter's trapped radiation, as well as a plasma analyzer, a magnetometer, two meteoroid experiments, an ultraviolet photometer, an imaging photopolarimeter and an infrared radiometer. Celestial mechanics and S-band occultation data will provide additional new results about properties of Jupiter and its satellites. Further details about the Pioneer F/G mission, spacecraft and experiments may be found in ref. 1.

Trapped Radiation Experiments

The Pioneer F/G experiments that provide data on Jupiter's energetic trapped particles are listed in Table I, together with the responsible experimenters and sponsoring organizations. Each of these experiments is described in turn, and estimates of the dynamic and energy E ranges for electrons and protons to nearly isotropic fluxes expected near the magnetic equator in the peak flux regions are given on Figures 3 and 4, respectively. Except as indicated, and where it must be specified, a 1024-bps telemetry rate is assumed. Figures 3 and 4 are arranged to show as vertical lines the energy thresholds (energy ranges in a few cases) for direct excitation of the various experiments. Detector saturation values are given as near-horizontal lines that are read on an ordinate scale of integral fluxes. The lower limits to the dynamic ranges of the experiments generally is below the lower edge of these graphs and is typically set by backgrounds from the RTGs or detector noise currents. The dynamic ranges for counting experiments are as large as $\sim 10^6$ for the UCSD solid state detectors. For experiments with integral responses, the intersection on these Figures of the graph of an integral spectrum with the vertical line representing the threshold of a detector indicates the fraction of saturated response of the detector due to that incident spectrum alone, if the value of the ordinate at this intersection is divided by the value of the ordinate giving the approximate maximum

Table 1. Pioneer F/G Experiments Bearing on Jupiter's Trapped Radiation

EXPERIMENT	WEIGHT (lb)	POWER (W)	PRINCIPAL INVESTIGATOR — ORGANIZATION
Trapped Radiation Detector	3.8	2.9	R. W. Fillius — UCSD
Geiger Tube Telescopes	3.6	0.8	J. A. Van Allen — University of Iowa
Cosmic Ray Telescopes	6.9	2.3	F. B. McDonald — NASA-GSFC
Charged Particle Detectors	7.2	2.2	J. A. Simpson — University of Chicago
Magnetometer	6.0	4.5	E. J. Smith — JPL
Plasma Analyzer	11.7	4.4	J. H. Wolfe — NASA-ARC

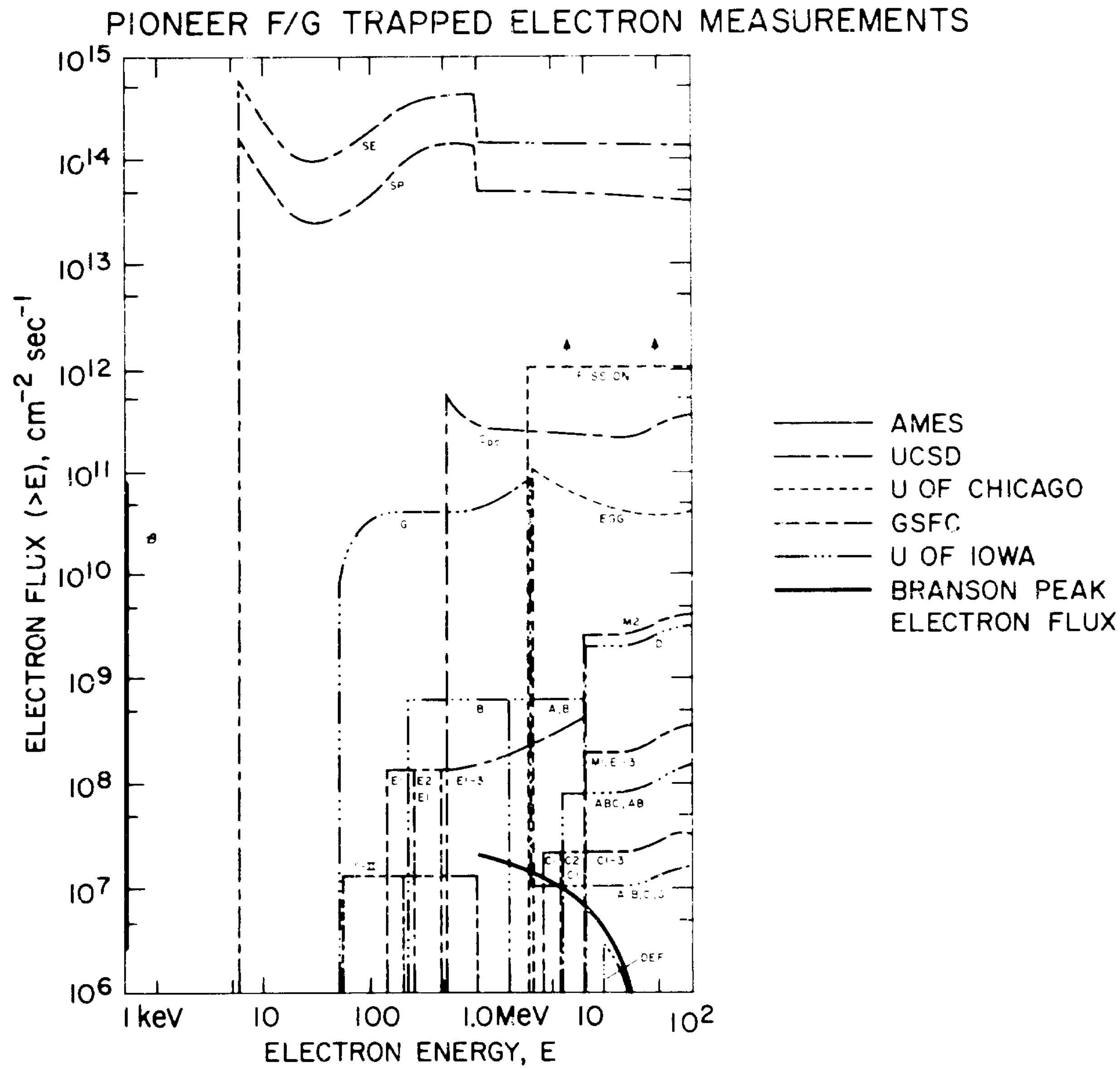


Figure 3. Energy Thresholds and Estimated Upper Limit Electron fluxes for the Pioneer F/G Energetic Particle Experiments

PIONEER F/G TRAPPED PROTON MEASUREMENTS

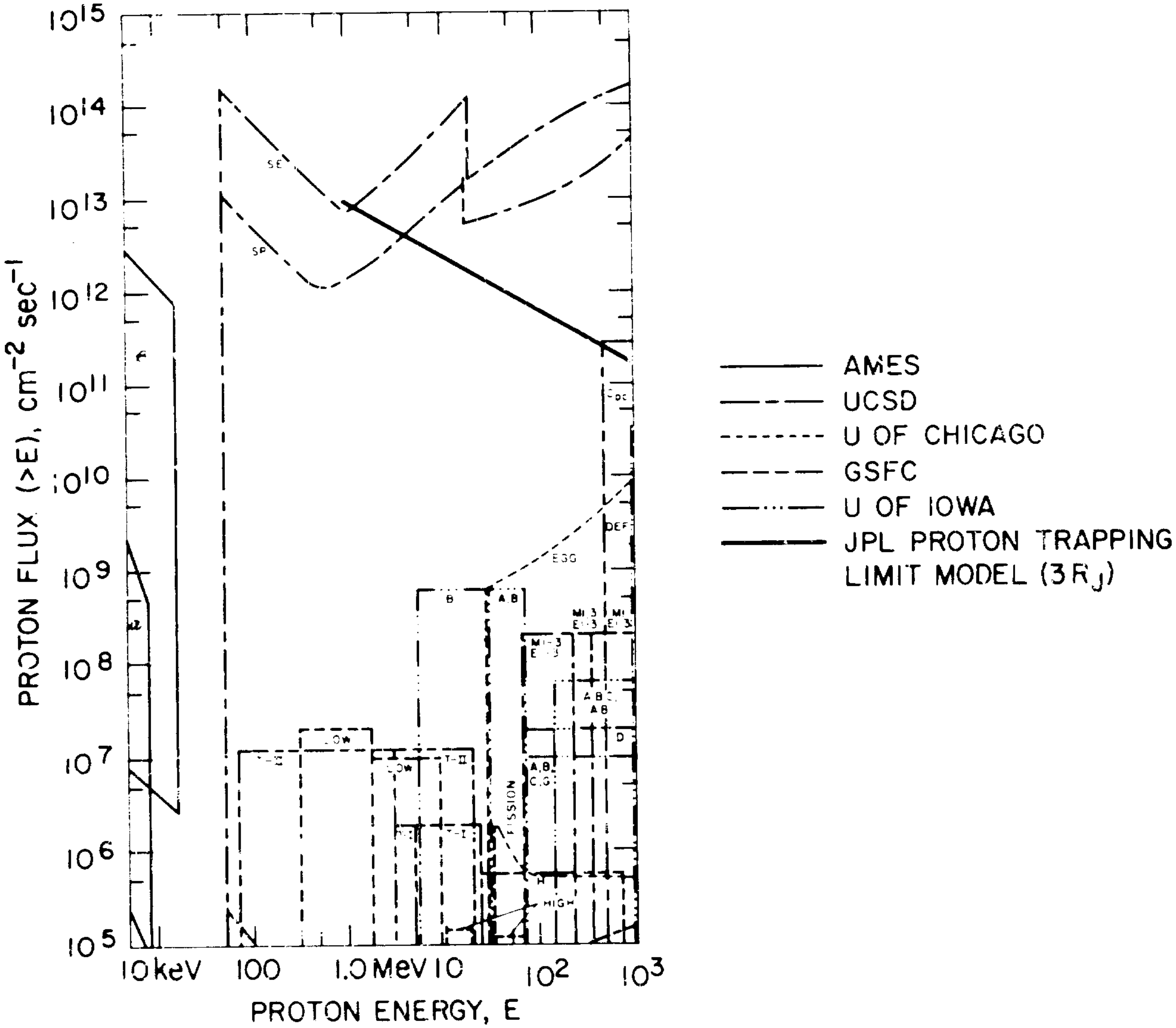


Figure 4. Energy Thresholds and Estimated Upper Limit Proton Fluxes for the Pioneer F/G Energetic Particle Experiments

response of the detector. The University of Iowa shower telescope discussed later is a partial exception near the threshold energy because of its pronounced energy-dependent response in this energy range. Experiments with true differential energy response characteristics such as the Ames Plasma Analyzer form a special case, as indicated later. Responses of these experiments to combined fluxes of protons and electrons are not specifically indicated on Figures 3 and 4, although such responses can be obtained from these two figures and are discussed later. Responses of the experiments to energetic positively charged particles other than protons are not considered here, although some of the counter telescopes possess capabilities for discriminating between energetic positive ions with different masses. The deviations of the saturation limits from horizontal lines represent estimated energy dependences of particle ranges, dE/dx, elastic electron scattering, bremsstrahlung production and electron shower production. Penetration of detector shielding by omnidirectional fluxes is indicated in many cases. Responses to bremsstrahlung from very steep electron fluxes is not indicated. The Ames Plasma Analyzer saturation values slope upward to the left because peak counting rates in each differential energy channel are indicated in the integral units of the ordinate. Figure 3 also gives the spectrum of the peak electron flux deduced by Branson (ref. 2), while Figure 4 gives a JPL trapping-limit model proton spectrum for 3 R_J. (On Figure 4, "HIGH" refers to responses of the University of Chicago Main Telescope.).

University of Iowa Experiment Package

The description of the individual detectors in the experiments begins with the University of Iowa shower detector, with response indicated by "DEF" in the lower right-hand corner of Figure 3. This detector is a triangular array located within a 7.2 g cm^{-2} lead shield of three Eon type 5107 Geiger-Müller (GM) tubes each with a 0.014 cm^3 detecting volume. A particle traveling in a straight line cannot pass through all three GM tubes so the triple coincidence counting rate due to shower secondaries produced in the lead by electrons with E > 20 MeV is used as a measure of omnidirectional electron fluxes with E > 20 MeV. It is estimated from published cross-sections of deuterons produced by 3 BeV protons incident on lead (ref. 3) that the overall response of this detector to 3 BeV protons is with an efficiency ~$10^{-2\pm1}$ times that of its response to ~40 MeV electrons, although precise values would have to be obtained with accelerator calibrations. The response to protons would be linear with energy in this energy range. The singles counting rate of one GM tube, D, in the shower array is available for determining accidental coincidence rates. This tube will respond both to electrons with E $\gtrsim$ 10 MeV and to protons with E > 65 MeV.

Three Eon type 6213 mica end-window GM tubes, each with a 0.027 cm^3 detecting volume, are arranged to form both a linear, three-element telescope and individual detectors of low-energy particles through the end windows. Tube A has a directional response both to electrons with E > 1.9 MeV and to protons with E > 30 MeV. Tube B has a directional response both to electrons with E > 0.22 MeV and to protons with E > 5.4 MeV. Tube C h[illegible] omnidirectional shielding and the same omnidirectional response as tubes A and B, to both protons with E > 73 MeV and to electrons with E > 6 MeV. The ABC and AB directional coincidences respond to particles moving along directions near that of the spacecraft spin axis, with proton energies $\gtrsim$ 130 MeV and electron energies $\gtrsim$6 MeV.

A fourth 6213 GM tube, G, is included in the University of Iowa experiment package. This tube is mounted in a scatter geometry and responds to directional fluxes of electrons with E > 50 keV that scatter from a gold surface. Tube G also responds to omnidirectional fluxes of both electrons with E > 3 MeV and protons with E $\gtrsim$70 MeV. The dynamic range of all the singles counting rates in the University of Iowa package is ~10^6, with reduced accuracy in the highest decade. Responses of all these detectors are indicated on Figures 3 and 4.

University of California, San Diego (UCSD) Experiment Package

A fully depleted silicon surface-barrier solid state detector, 1-mm thick and 3-mm in diameter, in a scatter geometry, similar to the University of Iowa GM tube G, is included in the UCSD package. Three energy thresholds for scattered electrons, E_1, E_2 and E_3, at 0.09, 0.19 and 0.4 MeV, respectively, are provided for directional fluxes of electrons that scatter from a gold surface. Thresholds E1-3 also respond to omnidirectional fluxes both of electrons with $E > 10$ MeV and of protons with $E > 68$ MeV. This detector has a dynamic range of $\sim 3 \times 10^6$.

A solid state detector identical to the one in the scatter geometry, but with two higher energy thresholds and totally shielded, is also included. Its thresholds, M1, M2 and M3 are 0.4, 0,85 and 1.8 MeV, respectively. The M3 threshold does not respond to electrons directly, but only to omnidirectional fluxes of about 68- to 350-MeV protons. The M1 threshold responds to the same combination of omnidirectional fluxes as threshold E3 for the scatter geometry solid state detector. The M2 threshold must respond to omnidirectional proton fluxes of about 68 to 230 MeV, and directional fluxes of both protons with $E > 230$ MeV and electrons with $E > 10$ MeV. but these directional responses must not be very pronounced. This detector has a dynamic range of 10^7.

The UCSD package also contains two thin scintillators viewed by vacuum photodiodes. Detector SE is a Pilot B plastic scintillator with a thickness of about 0.5 mil. This scintillator responds to directional fluxes of both electrons with $E > 5$ keV and protons with $E > 50$ KeV, but the proton (and heavier positive ion) response is less efficient than the electron response because intrinsically, light production from plastic scintillators is saturated by the slow positive ions because of their high values for the rate of energy loss. Detector SP is a ZnS(Ag) screen about 4 microns thick, for which the positive ion light output exhibits much less saturation. Both of these detectors respond to omnidirectional fluxes of both electrons with $E > 1$ MeV and protons with $E > 20$ MeV. The SE and SP detectors have a dynamic range of 10^9.

The final detector in the UCSD package is an alcohol/water Čerenkov radiator viewed by a photomultiplier tube. A dc-current measurement from the seventh dynode, C_{dc}, and three pulse height analyzed channels, C1, C2 and C3, respond to directional fluxes of electrons with energies above ~0.5, 4,6 and 10 MeV, respectively, as well as to directional proton fluxes of >0.5 and ≥7.4, 11 and 18 BeV, respectively. There will probably be some background effects associated with the highly sensitive photomultiplier tube. The electrometer amplifier (which measures both the seventh dynode current from the photomultiplier and the SE and SP photodiode outputs) is periodically calibrated in flight. This detector has a dynamic range of 10^6.

University of Chicago Experiment Package

The University of Chicago package contains a fission foil of Th^{232}, approximately 4 mils thick, viewed by two curved silicon surface barrier detectors, each with a 25-micron by 14.7-cm^2 active volume. Two high-energy discriminator settings (30 and 50 MeV) are used for detection of the fission fragments. This detector will respond to omnidirectional fluxes of energetic protons with E > 30 MeV, although the response depends on the energy spectrum of the incident protons. For proton fluxes $\geq 10^{-3}$ times the electron flux, the proton-induced fission rates are believed to dominate those due to electron- and photo-induced fissions, as well as those due to neutrons produced from nuclear reactions with the spacecraft matter. This detector has a dynamic range of 4×10^5 at 512 bps.

This package also contains an electron and bremsstrahlung detector (EGG) consisting of a beryllium shielded silicon surface barrier, solid state detector, 1 mm thick and 2.8 cm^2 in area, operating in a current mode. The shield is 1.07 gm cm^{-2} thick, so the detector responds directly to omnidirectional fluxes of electrons with $E \gtrsim 3$ MeV, and protons with E >30 MeV The detector is calibrated in flight using three pinlite lamps located within the beryllium shield. The solid state detector must be at a temperature less than -40°C in order to provide accurate measurements; the temperature is included in subcommutated measurements so that it is continually read out. This detector has a dynamic range of 10^7.

The University of Chicago package also contains a shielded, three-element low-energy solid state detector telescope (LOW) which responds to directional proton fluxes with energies between 0.3 and 9 Mev. The first element in the telescope, L1, is a fully depleted silicon surface barrier detector, 34 microns thick with a 1.0 cm^2 area. The remaining two elements are both lithium drifted detectors connected together to form a single element electrically, L2. The first of these two lithium drifted detectors is annular, with an 850-micron sensitive thickness, and inner and outer diameters of 25.4 and 28.2 mm, respectively. The surface barrier detector is located within the annular detector which acts as a guard. The final lithium-drifted detector has a 400-micron sensitive thickness and an area of 2.3 cm^2. Protons with energies between 0.3 and 1.6 MeV that enter detector L1 are stopped in it. Protons with energies between 1.6 and 9 MeV will be counted in a coincidence mode between detectors L1 and L2. Proton events will appear in nine channels, each 0.18 MeV wide, in a 32-channel pulse height analysis of energy deposits in detector L1; the remaining channels are devoted to heavier nuclei (α particles). The dynamic range of this detector is on the order of 10^5. This telescope permits clean measurement of low energy protons in the presence of the background neutron and gamma fluxes from the RTGs.

The final detector in this package is the main telescope. This is a 7-element, solid state detector array arranged with five lithium drifted solid state detectors, and a conical CsI scintillator viewed by a lithium drifted photodiode, all forming the telescope that is surrounded by a plastic scintillator guard viewed by a photomultiplier tube. The CsI-photodiode combination is located before the final solid state detector that terminates the telescope array. Beginning with the front end of the telescope and including the photodiode, the detectors have the following characteristics: 0.75 mm sensitive depth by 3.8 cm^2 sensitive area curved, 1.5 mm sensitive depth by 4.9 cm^2 sensitive area curved, and sensitive volumes 0.85 mm thick by 7.3 cm^2, 1.0 mm thick by 1.9 cm^2, 0.5 mm thick by 6.3 cm^2 (photodiode) and 1.0 mm thick by 7.3 cm^2. The conical CsI scintillator is about 1.3 cm thick. The plastic scintillator guard is 9.5 mm thick and 91.3 mm high, in the form of a cylindrical shell enclosing the other elements of the telescope. This experiment has the capability of deleting three of the detectors on command if they should fail, and also of a certain accommodation in the logic in the event of detector failure. Pulse height analysis with 256 channels is performed for any one of 13 logic conditions, for one particle every other spacecraft telemetry frame. There is a provision for choosing upon command between two weighting conditions for the logic that determines energy deposits that are pulse-height analyzed. This telescope permits measurement of the spectra of cosmic ray nucleons with charge Z= 1 to 8. Also, low energy electron responses are excluded from the two-dimensional pulse height analysis by a slant discriminator.

The maximum main telescope counting rate without overflow at a 512-bps telemetry rate for each energy range of protons or electrons corresponds to integral fluxes below the lowest value of the ordinates of Figures 3 and 4, except for two cases. These integral limits for directional fluxes of protons are $\leq 1.4 \times 10^5$ cm^{-2} sec^{-1} for the 10 to 19 MeV energy range, $\leq 1.2 \times 10^5$ cm^{-2} sec^{-1} for the 32 to 68 MeV range, ≤ 110 cm^{-2} sec^{-1} for the 3 to 10 MeV range and ≤ 180 cm^{-2} sec^{-1} for $E \geq 68$ MeV. For electrons, these limits are ≤ 86 cm^{-2} sec^{-1} for the 1 to 3 MeV energy range and $\leq 1.2 \times 10^5$ cm^{-2} sec^{-1} for the 6 to 12 MeV energy range. The low flux limits reflect the emphasis given to measurements of galactic and solar cosmic rays by this experiment. The plastic scintillator singles count rate and five main telescope count rates corresponding to energy ranges of protons and electrons just given are data outputs in addition to the 256-channel pulse height analysis outputs.

NASA-Coddard Space Flight Center Package

The Goddard package contains three solid state detector telescopes. All of the solid state detectors are fully depleted units. One telescope, T-II, is shielded. Most of this package's count-rate telemetry at the encounter with Jupiter is allocated to Telescope T-II. This shielded telescope has three elements. Beginning at the entrance aperture, the first element is a 50-micron thick, 50-mm^2 area silicon surface barrier detector; the second is a 2.5-mm thick, 50-mm^2 area lithium-drifted silicon detector with an annular guard detector built-in that surrounds the edge. The final element is a 2.5-mm thick, 200-mm^2 lithium drifted silicon detector. Four energy ranges of directional fluxes of both protons (from 0.05 to 3 MeV) and electrons (from 0.05 to 0.15 MeV) that stop in the first detector,and four more energy ranges of directional fluxes of electrons with energies (ranging from 0.15 to 1 MeV) that stop in the second detector, are each measured. Four coincidence counting rates between the first and second detectors, due to protons with energies between 3 and 20 MeV, are measured in addition. In the interplanetary mode, alpha particles in the first detector of this telescope are identified and measured.

A second low-energy telescope, T-I, contains four solid state detectors. Beginning at the entrance aperture, the first two are silicon surface barrier detectors; each one is 100 microns thick and 100 mm^2 in area.

The final two are lithium drifted silicon detectors, both 2.5 mm thick with about three times the area of the first two detectors. During planetary encounter, this telescope will measure coincidence count rates due to directional fluxes of 3 to 5 and 5 to 22 MeV protons. A 1024-channel pulse height analysis gives one energy deposit from one detector at an average rate of once each 64 spacecraft telemetry frames during planetary encounter.

The final unit in this package, the high energy telescope, H, contains seven lithium drifted silicon solid state detectors. The first two are each 300 mm^2 in area and 2.5 mm thick, while the third telescope element is made up of two stacks, each of two 2.5 mm thick, 850 mm^2 area detectors. The final detector is similar to these last four. During planetary encounter, this telescope gives the octant of origin for 15 particles during every 128 telemetry frames, as well as the energy deposited by the particle in one of two detectors, the first or the last.

Other Pertinent Spacecraft Experiments

In addition to the data from the four energetic particle experiments, the plasma analyzer and magnetometer measurements will bear on Jupiter's energetic trapped radiation. The magnetometer is a helium vector type that makes three-axis measurements in eight ranges from $\pm 2.5 \times 10^{-5}$ to ± 1.4 G. Pitch angle distribution measurements by experiments on the spacecraft require a knowledge of the orientation, location and strength of Jupiter's magnetic dipole, and the instantaneous orientation of the field relative to the spacecraft. All of this information is to be obtained from the magnetometer experiment. Knowledge of the magnetic field parameters also permits, in the absence of direct measurements of the radiation, both a relation with Earth-based measurements of Jupiter's decimetric radio noise and accurate calculations of the maximum energy densities of trapped particles that the magnetic field can contain. This information would improve present estimates of Jupiter's trapped radiation. The relation with Earth-based measurements of radio noise is based on the likely assumption that synchrotron radiation of trapped electrons is the origin of the noise, since the rate of energy loss of a gyrating electron, $\dot{U}$, for $P_{\parallel} = 0$, is proportional to $B^2 P_{\perp}^2 Q^4$ where $P_{\parallel}$ and $P_{\perp}$ are the components of the particle's momentum parallel and perpendicular to the magnetic field direction, respectively, B is the magnetic field strength and Q is the charge-to-mass ratio.

The plasma experiment uses two separate 90-degree deflection spherical electrostatic analyzers. The energy resolution of the high resolution analyzer, α, is $\leq 15\%$. Twenty-six continuous channel multipliers are used for detection of 0.1 to 8 keV protons. A medium resolution analyzer, β, uses five targets connected to electrometer amplifiers for detection of 0.1 to 16 keV protons and 2 to 500V electrons. The energy resolution is $\leq 22\%$. Where the plasma analyzer is turned on within Jupiter's magnetosphere, the peak fluxes of particles within its energy and dynamic range, indicated on Figures 3 and 4, will be measured. Magnetospheric plasma densities can govern the shape of Jupiter's distant field lines (refs. 4, 5) and possibly govern wave energies that interact with energetic particles in a self-limiting fashion (refs. 6, 7, 8).

Pitch Angle Distributions at Jupiter

The Pioneer F/G experiments that give pitch angle distribution information at Jupiter are listed in Table II, together with the energy ranges for protons and electrons, the half-angles of directional response, and the directions that are reported. It should be noted that the half-angle of the loss cone at the magnetic equator and 3 R_J jovicentric distance is 8°. For the expected spacecraft spin and telemetry rates of 5 rpm and 1024 bps, respectively, only the University of Iowa pitch angle measurements have adequate angular resolution for deducing trapped particle flux distributions at high latitudes along Jupiter's magnetic field lines.

Capabilities for Unambiguous Identification of Energetic Protons at Jupiter

Consideration of future missions leads to the question of the ~0.1 to ≥1 BeV proton flux information available from Pioneer F/G in the presence of the peak energetic electron fluxes with E > 1 MeV inferred from

Table II. Pioneer F/G Pitch-Angle Distribution Measurements at Jupiter

PIONEER F/G
PITCH-ANGLE DISTRIBUTION MEASUREMENTS AT JUPITER

EXPERIMENT	DETECTOR	PARTICLE/ENERGY	HALF ANGLE OF RESPONSE	ANGLES REPORTED
UCSD	CERENKOV	e^-: 0.75, 4, 6, 10 MeV p^+: > 480 MeV, > 7 BeV	~60°	EACH OCTANT (5 rpm SPIN RATE, ≥ 128 bps)
	SCATTER SSD	e^-: > 0.09, 0.19, 0.4 MeV	~22°	
	PLASTIC SCINT. ZnS SCINT.	e^- > 5 keV p^+: > 50 keV	25°	
U. OF CHICAGO	HIGH ENERGY TELESCOPE	p^+: 3-10 MeV 10-19 MeV	~60° 32°	IDENTIFY OCTANT OF ONE PARTICLE EVERY OTHER MAIN FRAME
		32-68 MeV	24°	OPTIONAL PRIORITY FOR CHOSEN PARTICLE
		e^-: 6-12 MeV	24°	256 CH. PHAS
U. OF IOWA	GEIGER TUBE (A)	e^-: > 1.9 MeV; p^+: > 30 MeV	15°	EVERY ~6° FOR 1024 bps, 5 rpm SPIN RATE
	GEIGER TUBE (B) SCATTER GEIGER TUBE	e^-: > 0.22 MeV; p^+: > 5.4 MeV e^-: > 50 keV	15° ~15°	GROUND SYNTHESIS ONLY OF PITCH ANGLE DISTRIB.
GSFC	LOW ENERGY TELESCOPE-II	e^-: 0.15-1 MeV; p^+: 0.05-3 MeV	15°	EACH OCTANT (4 ENERGY LEVELS EACH FOR e^- AND p^+)
	LOW ENERGY TELESCOPE-I	p^+: 3-5, 5-22 MeV	25°	EACH OCTANT
	HIGH ENERGY TELESCOPE	p^+: 20-800 MeV	~9°	OCTANT, 1024 CH. PHA, BOTH FOR 15 PARTICLES EACH 128 MAIN FRAMES
AMES	ESA A, NEXT TO END CHANNELS	p^+: 0.1-8 keV	~2.9° × ~1°	PEAK FLUX TO 1/512 OF SPACECRAFT SPIN PERIOD
	ESA B, END TARGETS	p^+: 0.1-16 keV; e^-: 2-500 V	~4.4° × 24°	

radio noise measurements. Inspection of Figures 3 and 4 reveals that the M3 threshold of the UCSD shielded solid state detector gives the flux of protons with energies between 68 and 350 MeV and this detector is nominally insensitive to electrons above threshold M3. This is an omnidirectional measurement. Threshold M3 could still be saturated by background sources such as bremsstrahlung from intense fluxes of electrons with energies less than 1 MeV. Barring the possibility of saturation of this detector by such indirect backgrounds, another omnidirectional proton flux measurement for energies between 68 and 230 MeV should be available from threshold M2 in the same experiment package, when the contribution to the count rate of both protons with E > 230 MeV and electrons with E > 10 MeV are subtracted. The interfering electron flux should be available from the UCSD Cerenkov detector or the University of Iowa shower detector, DEF, and GM tube D, as indicated below, while the interfering proton flux should be available from the M3 threshold. The combination of the University of Chicago fission and 'EGG' detectors will give another measure for energetic proton fluxes above 30 MeV, and consequently perhaps in the 0.1 and 1 BeV range of energies, although details of the energy discrimination characteristics of the fission detector for incident proton fluxes have not yet been published. Similarly, the combined responses of the Iowa ABC or AB responses, which have proton thresholds of ~130 MeV, and the C2 Cerenkov detector, which has a proton threshold of ~11 BeV, while both have ~6 MeV electron thresholds, should give the flux of protons above ~130 MeV. The best proton measurements just described should all be nearly omnidirectional in nature, so there is only limited capability for pitch angle measurements of protons to give flux distributions away from the near-equatorial region where the spacecraft will pass. The University of Iowa GM tube A will give excellent pitch angle measurements of protons with E > 30 MeV, if it is not swamped by directional electron fluxes with E > 1.9 MeV, omnidirectional fluxes of both electrons with E > 10 MeV and protons E > 73 MeV and bremsstrahlung.

The Pioneer F/G measurements will not give direct information about trapped fluxes closer to Jupiter than the distance of closest approach. Models of Jupiter's trapped radiation for these inner regions will have to be built up from extrapolations of the Pioneer measurements. In the case of the trapped electrons, more accurate interpretations of radio noise measurements from Earth in terms of electron fluxes should be possible when the new planetary data is available from Pioneer.

Theoretical Considerations

Many uncertainties can be considered when experimental responses during the first encounter of Jupiter's energetic trapped particle population are estimated. There are various estimates for energetic trapped electron populations (energies generally >1 MeV) but in the case of protons and of electrons with energies lower than ~1 MeV, accurate estimates appear to be difficult at this time. The reason for this is basically that analogies with the largest region of Earth's trapped radiation, where radial/pitch angle diffusion mechanisms seem dominant, can only be based at this time on theoretical models which in turn still rest significantly on *ad hoc* features resulting from observations at Earth. Assumptions that various parameters in models for Earth's trapped radiation are unchanged within limits between the cases of Earth and Jupiter would result in models for Jupiter's trapped radiation that have been explored to only a small extent to date. There are additional features for which more direct analogies with the case of Earth probably are available, that probably will be less prominent in Jupiter's trapped radiation; these would include the details of the interaction of trapped radiation with the atmosphere, the manifestation of non-conservation of the first adiabatic invariant of the particles' motions and proton injection due to the decay of solar and galactic cosmic ray albedo neutrons. Some features more peculiar to Jupiter, such as the presence of satellites within the magnetosphere that must form a significant additional location for loss of trapped radiation, could probably be assimilated as details within a more generalized theory for magnetospheric particle energization.

Expressions for stable trapping limits of charged particle energies for particles in a static dipole magnetic field have been published (refs.9, 10). Observation of these limits has been reported for the most energetic protons in Earth's trapped radiation (E > 350 MeV) (ref. 11), but more severe limits are found empirically for 40 to 110 MeV protons (ref. 10), presumably due to nonstability of the dipole field for the smaller gyroradii particles at some locations. Maximum distances for several energies of equatorially mirroring protons are given in Table III, using the stronger limit given in reference 10.

Table III. Maximum Distances for Stable Trapping at the Equator of a Static Dipole Field

Proton Energy, MeV	Distance, R_J*	Distance, R_J†
10^2	58	~150
10^3	31	84
10^4	12	33
10^5	4.0	11
10^6	1.3	3.5

*For a surface equatorial field of 7 G; †for an equatorial field of 1.9G at $3R_J$.

These values provide additional constraints on fluxes in trapping limit models for hypothetical proton fluxes at Jupiter, than the usual considerations of magnetic and trapped energy densities alone.

The energies for stable trapping drop rapidly for nonequatorial mirror points. For a field line with a 3 R_J equatorial distance, the latitude of the intersection with the visible surface of the planet is ~55 degrees. The maximum stable trapping energies for protons mirroring on this field line at latitudes of 0, 23 and 43 degrees are 180, 90 and 17 BeV respectively, with a 7 gauss equatorial field at the surface of the planet. The maximum energies for electrons and alpha particles mirroring at the equator on this field line are 300 MeV and 89 BeV per nucleon, respectively. Evidently radiative losses would prevail before electrons trapped in Jupiter's magnetic field could reach a 300 MeV energy.

Numerous summaries of ideas on the relation of pitch angle and radial diffusion to the bulk of Earth's trapped radiation have recently appeared. Kennel (ref. 13) reemphasized limits on Earth's trapped particle fluxes due to wave-particle interactions, and the role of pitch angle diffusion, for which both strong and weak limits are identified formally. The relative importance of radial and pitch angle diffusion has been discussed by

Haerendel (ref. 7), who also indicates that Earth's plasmapause ought to form one type of boundary for energetic trapped particles. Roberts (ref. 14) reviewed experimental evidence from Earth's trapped radiation for pitch angle diffusion, and indicated mechanisms for pitch angle scattering in terms of cyclotron and bounce (ref. 15) resonances. Williams (ref. 16) reviewed a more general and more recent class of measurements of Earth's trapped particles. Considering the outer-zone protons and, during magnetically quiet periods, the outer-zone electrons, he concluded that cross-L diffusion is the dominant dynamic process, although for the electrons even during quiet times, consideration of pitch angle diffusion is also required. Earth's outer-zone electrons require special consideration since if geomagnetic activity were low enough for many weeks they would almost disappear (see ref 14). Radial diffusion appeared to be the source of outer-zone low-energy protons when for 0.2 to 0.5 MeV energies, L^3E was observed to be constant (ref. 17). Here L is the equatorial crossing distance of the magnetic field line. Walt (ref. 18) has identified significant needs for radial diffusion mechanisms in interpreting both Earth's inner and outer radiation zones. His summary of radial diffusion coefficients that includes the most recent results does not reveal a great difference between values for protons and those for electrons. A recent summary by Fälthammar (ref. 19) of the same general ground indicates that lack of adequate measurements of electric and magnetic field fluctuations in Earth's magnetosphere is still the main block to increased understanding of the steady-state dynamics of Earth's trapped radiation. An analysis of complications when particle fluxes are to be mapped in the outer region of Earth's magnetosphere where the magnetic field is distorted appreciably due to external currents is available (ref. 20). A correct treatment of the outer regions, including magnetospheric electric fields, is particularly important when radial diffusion of particles is considered, because this mechanism often is thought to involve particle transit from without the magnetosphere inward through regions of distorted magnetic field to where the highest energies are found.

The The discussions referred to above indicate that radial diffusion is believed to be a significant source of Earth's energetic trapped particles, but pitch angle diffusion must usually be included to match observations. Values for diffusion coefficients have been determined many times.

Models for Jupiter's radiation could be calculated using analogies with the ideas that have been developed for the case of Earth. It would seem that these models would be indefinite until even such basic information as the size of Jupiter's magnetosphere and the basis for choosing values of diffusion coefficients become known. Some believe that there are still significant gaps in the existing knowledge of the situation at Earth in order to have consistent theories. However, the record of the observations alone (of Earth's trapped radiation) clearly reveals its morphology, particularly in the energy ranges that must be considered for estimating degradation of spacecraft systems.

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DISCUSSION

DR. WHITE: How many of these detectors will give directional information in the region of 10^7 electrons cm^{-2} sec^{-1} at 5 MeV?

DR. MIHALOV: The Cerenkov detector gives directional information for electron fluxes above various thresholds which include 5 MeV; the half-angle of its response is rather broad.

DR. WHITE: The point I am making is: are they really directional when they are in a flux of electrons coming from all directions of that intensity?

DR. MIHALOV: The answer to your question hinges upon the detailed calibration data, which I don't have. I don't know what the response of that detector would be if electrons were incident upon it with that flux and not in the sensitive direction.

DR. WHITE: Suppose they are all 5-MeV electrons at 10^7 cm^{-2} sec^{-1}--wouldn't that give bremsstrahlung like 10^4 cm^{-2} sec^{-1} for any shield? So, one has a real problem.

DR. MIHALOV: The bremsstrahlung will excite the photomultiplier directly; that is true. (Ideally) It will not give direct pulse outputs due to conversion in the Cerenkov radiator for the non-sensitive direction.

I have already mentioned that the University of Chicago telescope has a low capability for not saturating the logic, so in the flux that you have mentioned, it is not likely that it will give electron spectra. The solid-state detectors in that experiment are rather large.

MR. PARKER: Don't they have the capability of going to a lower number of channels to improve that situation some?

DR. MIHALOV: I think that the matter here is the noise current through the detector rather than the number of channels that they use.

MR. PARKER: What I am saying is that they can look at smaller and smaller regions of energy in order to help reduce their data flow.

DR. MIHALOV: For protons, they might be able to do that; but the electrons will give small energy deposits in those detectors. For electrons, they will be near a type of background that should yield increased currents due to bremsstrahlung depositing energy in the detectors. The details depend on what sort of amplifier the detector has. That experiment is designed basically for cosmic-ray studies and low counting rates. There is a good omnidirectional measurement of electrons above 20 MeV from the shower telescope. It is not on this list because it doesn't give directional information. The angular resolution is indicated by the lowest values for the angular response. I think the ones that Professor Van Allen now has in his experiment are certainly lower than the entries above; and these are about the same as the values for the Goddard experiment. He doesn't restrict himself to finding the octant origin of the particle, so, the best angular information from the spacecraft will be from the Iowa experiment.

DR. WHITE: Dr. Van Allen, will you also have that problem in the high electron flux?

DR. VAN ALLEN: Yes. But I have been using lithium fluoride targets in a Van de Graaf machine to get the decay electrons to end up under 13 MeV, so that the average value is about 5 MeV (roughly the value suggested). I can get a good angular distribution in the presence of that beam. I mean that the background of the shield encounters is very small compared to the open limit encounters, so I think it is a direct answer.

DR. WHITE: At what flux levels?

DR. VAN ALLEN: Well, this is sort of "zero flux levels," but insofar as the system is linear, it is good anywhere. The only place I can get into trouble is when I start saturating sectors. You suggested a flux of 10^7. I am still not in too bad a shape at 10^7, which is actually much higher than that, I would assume.

DR. KENNEL: I would like to make a couple of comments from the theorists' point-of-view: If you look at the proton energy coverage, it seems perfectly fine for theoretical considerations, but most of the detectors seem to have dynamic ranges with flux cutoffs on the order of 10^8 cm^{-2} sec^{-1}. From all we have heard, we would certainly love to go with some accuracy to 10^9. Following up on Dr. Brice's comment about to what extent it would be possible from Jupiter radiation-experiment measurements on Pioneer F and G, to construct a model that would enable you to predict what would happen in other regions of space, I would just like to make the remark that if the theorists had been around at the bloodletting of the design of the satellite, they would have insisted there be wave measurements on the satellite, so that you could get some idea of pitch-angle diffusion and energy loss processes.

DR. BRICE: I was about to ask facetiously for a plot of the wave amplitude as a function of frequency. I would bet that when we get all of the particle fluxes, we will say that if we just knew what the *waves* were doing, we would really know what was going on.

DR. SCARF: NASA Headquarters did have six Category One wave experiments to choose from.

DR. BRICE: Is there going to be no measurement even of the background levels in the telemetry receivers? Even that would be useful.

DR. SCARF: There is certainly an S-band receiver aboard.

DR. BRICE: With an AVC. If you just had the AVC level.

DR. NEUBAUER: What kind of resolution does the magnetometer have?

DR. SMITH: The maximum data rates you get are about 5 samples/sec, so near Jupiter, you should be able to measure frequencies up to about 1 Hz. There is a single-axis, three-channel spectrum analyzer that will cover the range from 10 kHz up to 10 Hz, so we got some information on 10 Hz. That is as far as we were able to go.

DR. KENNEL: Unfortunately, the proton cyclotron frequency is 10 kHz.

DR. SMITH: We miss it a little bit.

DR. MEAD: Will you get good replacements?

DR. SMITH: At the high frequencies, we will just get spectral information on the central axis, but we should get good vector information from 1 Hz on up.

MR. PARKER: The numbers that Dr. Mihalov showed are probably just the pure detector responses and not the system response of the whole spacecraft. I wonder if you have any feeling for upper limits in terms of the spacecraft as a system. What are these things going to be doing to the telemetry, etc?

DR. MIHALOV: The people who planned the spacecraft system used the Eggen model for electrons and protons. They thought that the protons in that model were negligible except for surface effects. They thought that any high-energy protons that might be there wouldn't appreciably change the danger picture compared with the electrons already there, so they felt that they had a chance of surviving with that model. The peak of that model was at $3R_J$, and the peak is about as high as some of your most reliable models. However, it drops off much more rapidly with distance going out, so the fluence is less.

MR. PARKER: You showed upper limits on the dynamic range. Is any information available on the lower limits?

DR. MIHALOV: The lower limits for detectors which are not arranged in coincidence with other detectors is basically due to background of galactic cosmic rays and the neutrons and gamma rays from spacecraft power supplies. For the case of Professor Van Allen's Geiger tubes, he placed the dynamic ranges at 10^7. The figures that I showed were somewhat more conservative. They assumed a dynamic range of about 10^6. The singles counting rates in solid-state detectors have various sizes for several reasons; spacecraft power supplies have been measured by several groups, in particular, the University of Chicago.

DR. KENNEL: Because of the large satellite orbital velocities and the co-rotation, there is likely to be a rather large (tens of km/sec) relative velocity between the plasma (and the plasmasphere) and the satellite that might possibly enable plasma probes designed for solar wind work to actually measure the density inside the Jupiter magnetosphere, which is a very interesting parameter. Could ARC measure a density of 100 cm^{-3} at a relative velocity of 20 km/sec with respect to the satellites? That is a flux of about 10^9.

DR. MIHALOV: I think that is below the sensitivity of the plasma probe.

DR. KENNEL: Is there any way of pushing down into that range in the time scale available?

DR. BRICE: Conceivably for Pioneer G, but certainly not for Pioneer F.

DR. WARWICK: John Wolfe told the Grand Tour's Science Advisory Group that the particle radiation would wipe out the possibility of observing anything.

DR. MIHALOV: He has a medium resolution detector which has current collectors, not channeltrons. The channeltrons are more sensitive, so I think the statement that was just quoted is a problem that he would face in attempting to make such measurements.

DR. SCARF: If we looked back at the history of magnetospheric particle measurements without channeltrons around the Earth, it would really be pretty dismal. It is certainly not an easy job.

CONCLUSION

Andrew J. Beck, Jr.*

INTRODUCTION

The overriding purpose of the final session of the Jupiter Radiation Belt Workshop was to establish a set of models for the Jupiter electron and proton trapped radiation belt which could be used in the determination of Outer Planets Mission spacecraft design requirements. Because of this engineering application, a radiation belt description was sought which would place bounds on the charged particle populations and energy. Thus, two models, each for the electron and proton components, evolved: a nominal or best estimate model, and an upper limit model.

The workshop models evolved from the papers presented, the discussion following each paper, and the contributions of all the participants at the final workshop session. The models are described by presenting the assumptions that most everyone agreed would be the best basis for the models at this time, then describing the models which were structured in the limited time available and concluding with the discussion which took place at the final session.

The selection of a set of postulates for the model basis that such a large group of highly qualified scientists and engineers can agree on is the principal result of the Workshop. Once this selection is made, a single set of internally consistent models can be deduced. Without this selection, a large number of models can be developed, depending on sources, loss mechanisms, acceleration processes, and transport schemes assumed. And, as long as the synchrotron radiation calculated from the particle populations and energies agrees with the observed synchrotron radiation, then there is really no reason to prefer one model over another model.

*Jet Propulsion Laboratory, Pasadena, California 91103.

Finally, the group recognized that certain limitations exist in our ability to formulate a highly reliable set of models at this time and that additional work and observational data (especially in situ data) are required before truly sound models can be constructed. The first in situ data will be available in December, 1973, from the Pioneer mission to Jupiter. In the meantime, the additional theoretical work, Earth-based radio observations, and the analysis of these observations can be performed which will contribute to our understanding of Jupiter. Another effort which contributes to our understanding is that undertaken to examine the internal consistency and to investigate the implications of the models. Because this effort is considered very important to the understanding of the models which were constructed at the Workshop, results, which have been made available in time for inclusion in these Proceedings, are given in a post-workshop Appendix.

MODELS FOR JOVIAN MAGNETICALLY TRAPPED ELECTRONS

Models for the energetic electrons trapped in the Jupiter radiation belt are based on the observed synchrotron radiation from Jupiter. Warwick has unfolded the particle energy and concentration from the observed synchrotron brightness temperatures. He calculates a characteristic energy near 6 MeV, and a peak flux of 2×10^7 electrons/cm^2-sec at L=2. However, the flux and the characteristic energy cannot be unfolded from the brightness temperature as a function of the L-shell parameter. Warwick assumed the solar wind with a trapping fraction of 10^{-9} as a source for the electrons and a particle concentration dependence of L^{-4} from the Davis and Chang[1] diffusion solution to connect the values at L=2 with values at the magnetopause (cf Warwick's paper*). Clearly, other sources are possible. Davis has pointed out that the acceleration of plasma electrons by electric fields produced by the interaction of the satellite, Io, with Jupiter's magnetic field is one possible source.

However, the completeness of the L-shell diffusion model with the possible conservatism that it contains led to general agreement that a model based on these assumptions was probably the best available for spacecraft design purposes.

[1] *Davis, L., Jr. and Chang, D. B., "On the Effect of Geomagnetic Fluctuations on Trapped Particles." J. Geophys. Res., Vol. 67, No. 6, pp. 2169-2179 (1962).*

* *References to paper(s) are those contained in these Proceedings.*

Consequently, the consensus was to select the following basis for the nominal trapped electron radiation belt model:

1) Earth-based observation of UHF flux density and/or brightness temperatures at various wavelengths and the interpretation of these data in terms of synchrotron radiation.

2) UHF beaming.

3) L-shell diffusion of electrons from values at L=2 connecting with solar wind electrons in the magnetosheath.

4) Conservation of the magnetic moment μ for electrons during the radial diffusion.

5) A planet-centered magnetic dipole producing an equatorial magnetic field strength of 10 gauss at a distance of 1 R_J.

6) No losses other than synchrotron radiation losses at small L values.

For the purpose of constructing a specific nominal trapped electron model, the numerical values computed by Warwick for the electron flux (2×10^7 electrons/cm^2-sec) and the electron characteristic energy (6 MeV) based on the first two assumptions were tentatively accepted. As a consequence of the third and fourth assumptions, the characteristic energy in the nonrelativistic case varies as L^{-3} and the differentail flux varies as L^{-3}, also. This latter dependence was misinterpreted in some of the discussion at the final Workshop session (cf footnote to Thorne and Coroniti paper).

It was agreed that the upper limit model for the trapped electron flux should be based on the same general assumptions as the nominal model. The difference between the models, it was felt, should arise from the uncertainty in the magnetic field strength, synchrotron beaming and unfolding of the synchrotron data. These uncertainties were interpreted as producing an increase of a factor of three in the electron characteristic energy and a factor of three in the electron flux at L=2. Thus, the upper limit model which was accepted has both the electron flux and the electron energy larger than the corresponding nominal model values by a factor of three. The general recommendation was made that relativistic corrections be made to the calculations for the characteristic energy and the flux.

The characteristic energy has been reevaluated by Davis (cf Appendix B). These results show that in the region of large L values where most electrons are nonrelativistic, the characteristic energy does have an L^{-3} dependence. Inside of this region, the dependence is less strong, eventually approaching an $L^{-3/2}$ dependence. In addition, the dependence of the integral flux is L^{-6}. This correction in the interpretation has been pointed out by Thorne and Coroniti (cf Thorne and Coroniti paper herein) and, by Davis (cf Appendix B). The revisions to the models based on these corrections has been summarized by Divine (cf Appendix B). The models that have resulted from these corrections are referred to as the post-workshop models.

Figure 1 shows models for the distribution of the electron flux in the equatorial plane of Jupiter's magnetosphere. The dashed lines are post-workshop models, and the solid lines are workshop flux models. The horizontal axis is the L-shell parameter, while the vertical axis is the flux of omnidirectional electrons having energy greater than zero for the model. However, fluxes of electrons having energy much less than the characteristic energy may also be present, as, for example, in a thermal plasma. Although this figure does not show the latitude dependence, the flux models are assumed to be latitude dependent, having an e-folding value of about 30 degrees.

The variation of the characteristic energy is shown in Figure 2 for the electron models. These electrons have been assumed to have a differential energy spectrum, given by

$$\frac{d\phi}{dE} = \phi_0\left[E/\left(E_0\right)^2\right]e^{-E/E_0}$$

where E_0 is the local characteristic energy. However, it should be pointed out that some evidence exists from the synchrotron emission data indicating an E^{-1} dependence. The horizontal axis represents the magnetic shell parameter, as evaluated either in or away from the magnetic equatorial plane, and the vertical axis

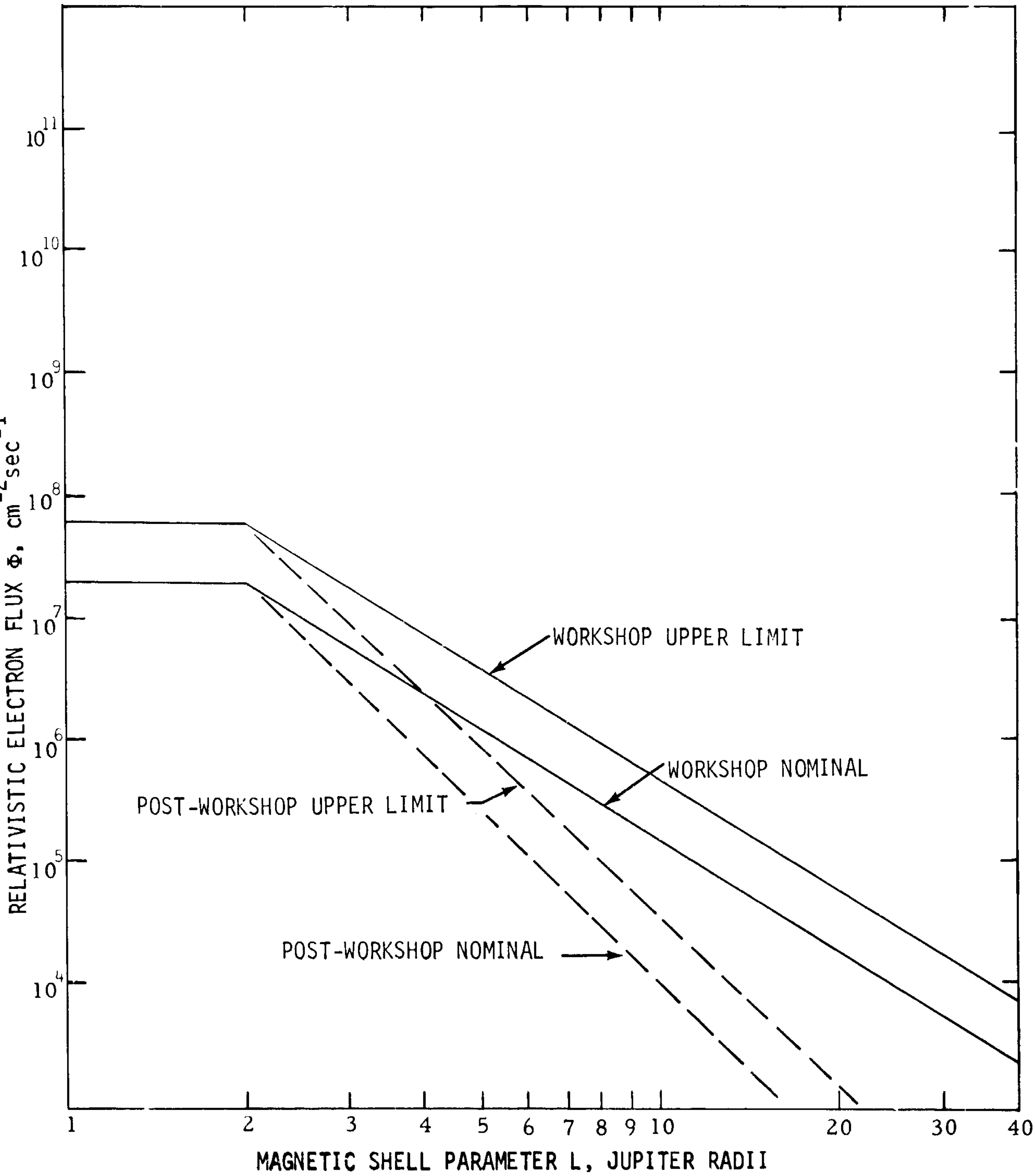

Figure 1. Model electron fluxes as functions of distance from the dipole in Jupiter's magnetic equatorial plane

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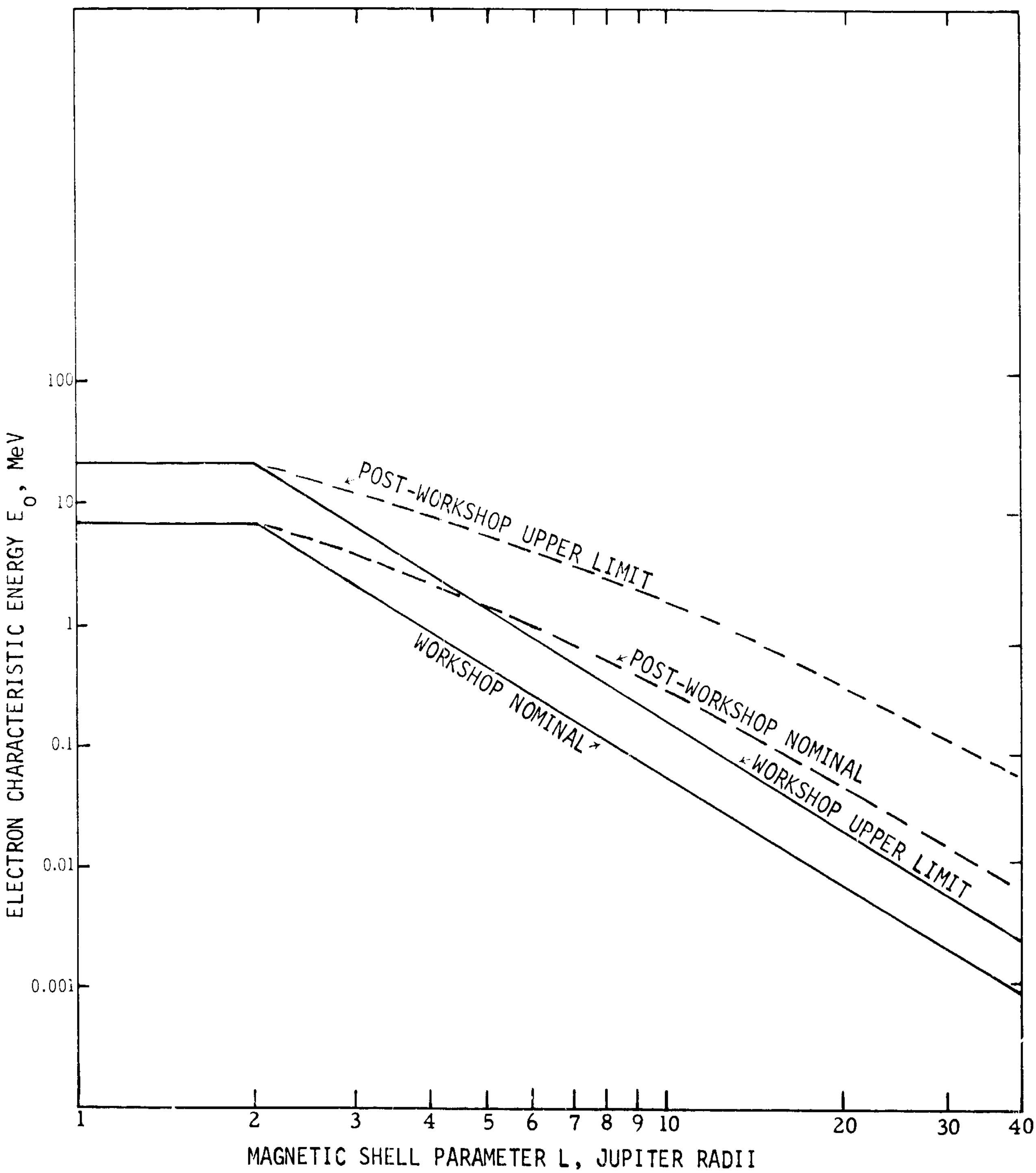

Figure 2. Model electron energies as functions of distance from the dipole in Jupiter's magnetic equatorial plane

represents the local characteristic kinetic energy of the electrons. The dashed lines represent the post-workshop relativistic results based on the recent analyses by Davis (cf Appendix B).

MODELS FOR JOVIAN MAGNETICALLY TRAPPED PROTONS

The workshop proton models are theoretical in nature. Furthermore, no observational data exists to confirm the existence of a Jupiter trapped proton radiation belt nor to limit the concentration of protons below the limit imposed by the maximum concentration that the magnetic field can contain. It was generally felt that a low flux of high energy protons near the planet could be deduced from the CRAND source and that if this calculation is performed properly, and losses (which include those produced by satellite shadowing) are taken into account, then the result will probably be a lower limit to the energetic proton population.

In the absence of any observational data from Jupiter's trapped proton radiation belt, the same physical processes which trap and accelerate electrons were assumed in formulating the nominal proton model. Thus, the nominal proton model assumes many of the features of the nominal electron model.

The consensus was to select the following basis for the nominal proton model:

1) L-shell diffusion of protons, from the magnetosheath all the way in to L=1.
2) Conservation of the magnetic moment.
3) Diffusion of protons past the satellites without interference.
4) A planet-centered magnetic dipole producing an equatorial magnetic field strength of 10 gauss at a distance of 1 R_J.
5) The assumption that the number density of protons is the same as the number density of electrons at L=2 in the workshop nominal electron model.
6) The assumption that the proton energy and energy density at L=2 is ten times the electron energy and energy density to account for the greater

solar wind proton energy expected at the magnetosheath.

7) No losses.

For the purpose of constructing a specific nominal trapped proton model, the values for the flux and the characteristic energy were fixed at L=2. The assumptions listed directly lead to a characteristic proton energy of 60 MeV and a flux of 7×10^6 protons/cm^2-sec. Similar to the case for the electrons, relativistic corrections could be made to the characteristic energy which was taken to have an L^{-3} dependence. However, in this instance, the correction was not important (cf Davis, Appendix B). However, again, the flux dependence was taken as L^{-3}. For the same reasons cited previously, the representation of the integral proton flux must be corrected to have the proper L^{-6} dependence.

The workshop upper limit proton model is based on the first four assumptions above with the additional assumptions:

1) A solar wind trapping fraction of 10^{-3}.

2) Ion-cyclotron instability considerations which limit the flux at intermediate L values.

The upper limit model relies heavily on the ion-cyclotron-wave instabilities presented by Kennel, Thorne, and Coroniti (herein). The characteristic energy was set at 100 MeV at L=2 and a spatial dependence proportional to L^{-3}, elsewhere. The flux at L=2 was equated to 3×10^9 protons/cm^2-sec based on the limiting ion-cyclotron instability limiting flux at L values between 8 to 10. The same corrections mentioned prevously were required for this model. All of these corrections are summarized in the paper by Divine (Appendix B). In making the correction to the upper limit proton model, the flux dependence derived by Thorne and Coroniti was used directly (cf Thorne and Coroniti paper).

Figure 3 shows various models for the distribution of the proton flux in the equatorial plane of Jupiter's magnetosphere. The dashed lines are post-workshop models and the solid lines are workshop proton flux models. The horizontal axis is the L-shell parameter, while the verical axis is the flux of omnidirectional protons having energy greater than zero for the model. However, fluxes of

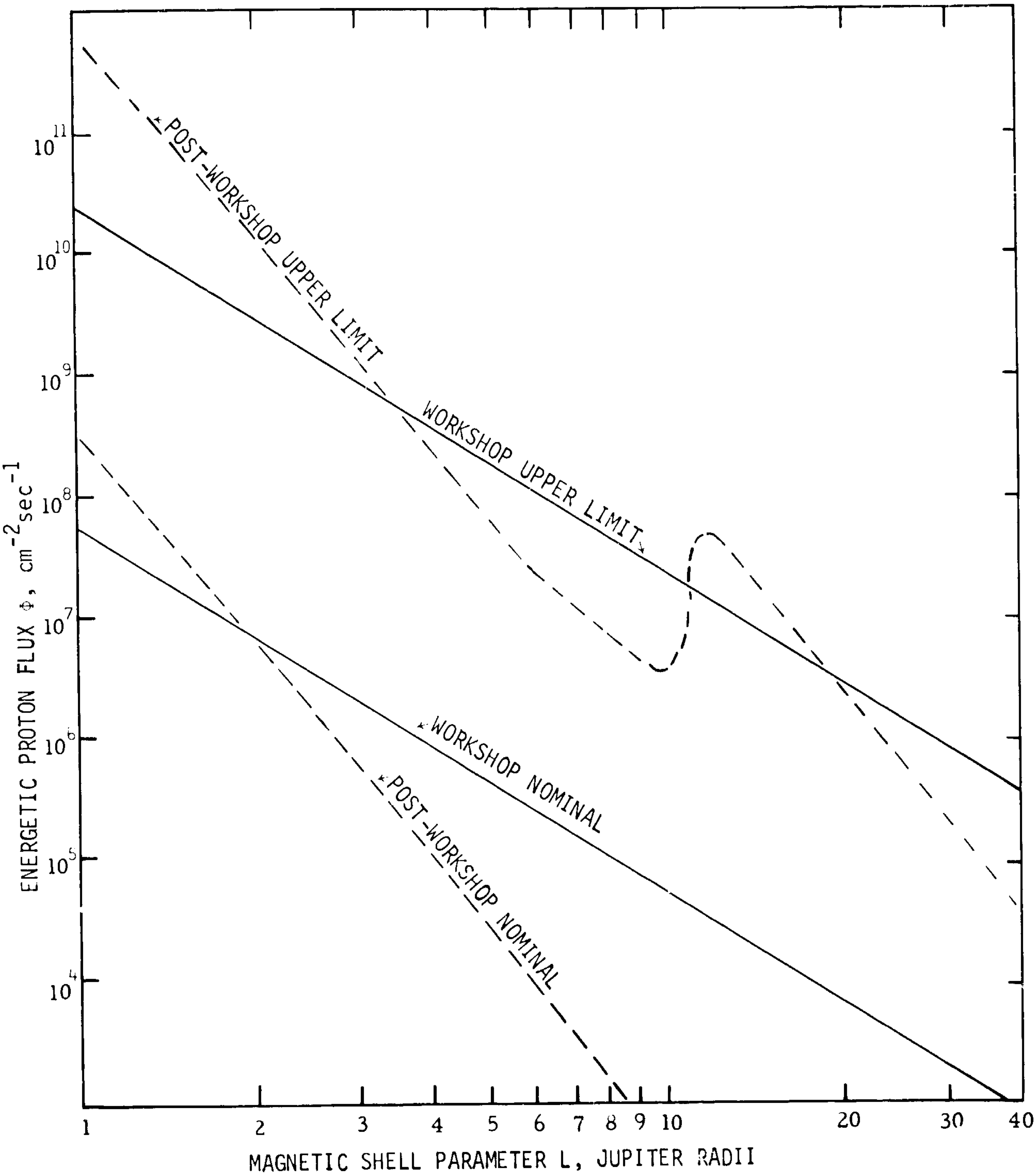

Figure 3. Model proton fluxes as functions of distance from the dipole in Jupiter's magnetic equatorial plane

protons having energy much less than the characteristic energy may also be present, as, for example, in a thermal plasma. The nearly three orders of magnitude difference between the two workshop models reflects the uncertainty in this environmental description. Although this figure does not show the latitude dependence, the flux models are assumed to be latitude dependent, having an e-folding value of about 30 degrees.

The variation of the characteristic energy E_0 with L is shown in Figure 4 for the proton models. The protons have been assumed to have a differentail energy spectrum, given by

$$\frac{d\phi}{dE} = \phi_0 \left[E/\left(E_0 \right)^2 \right] e^{-E/E_0}$$

where E_0 is the local characteristic energy. The horizontal axis represents the magnetic shell parameter, as evaluated either in or away from the magnetic equatorial plane, and the vertical axis represents the local characteristic kinetic energy of the protons. The dashed lines represent the post-workshop upper limit models.

RECOMMENDATIONS

The scientists and engineers who participated in the Jupiter Radiation Belt Workshop recognized that there are many uncertainties associated with constructing models for the energetic particles in the Jupiter magnetosphere. However, for the determination of design criteria for spacecraft missions to Jupiter, the consensus was to recommend the models given in the preceding paragraphs. This agreement generally contained the reservation that some aspects of the modeling problem be considered in greater detail. The general recommendation was made that those results requiring relativistic corrections be recalculated. The relativistic corrections for the conservation of the magnetic moment have been completed by Davis (Appendix B).

In addition, a recommendation was made to examine the consistency of the models and the implications of the existence of a trapped radiation belt at

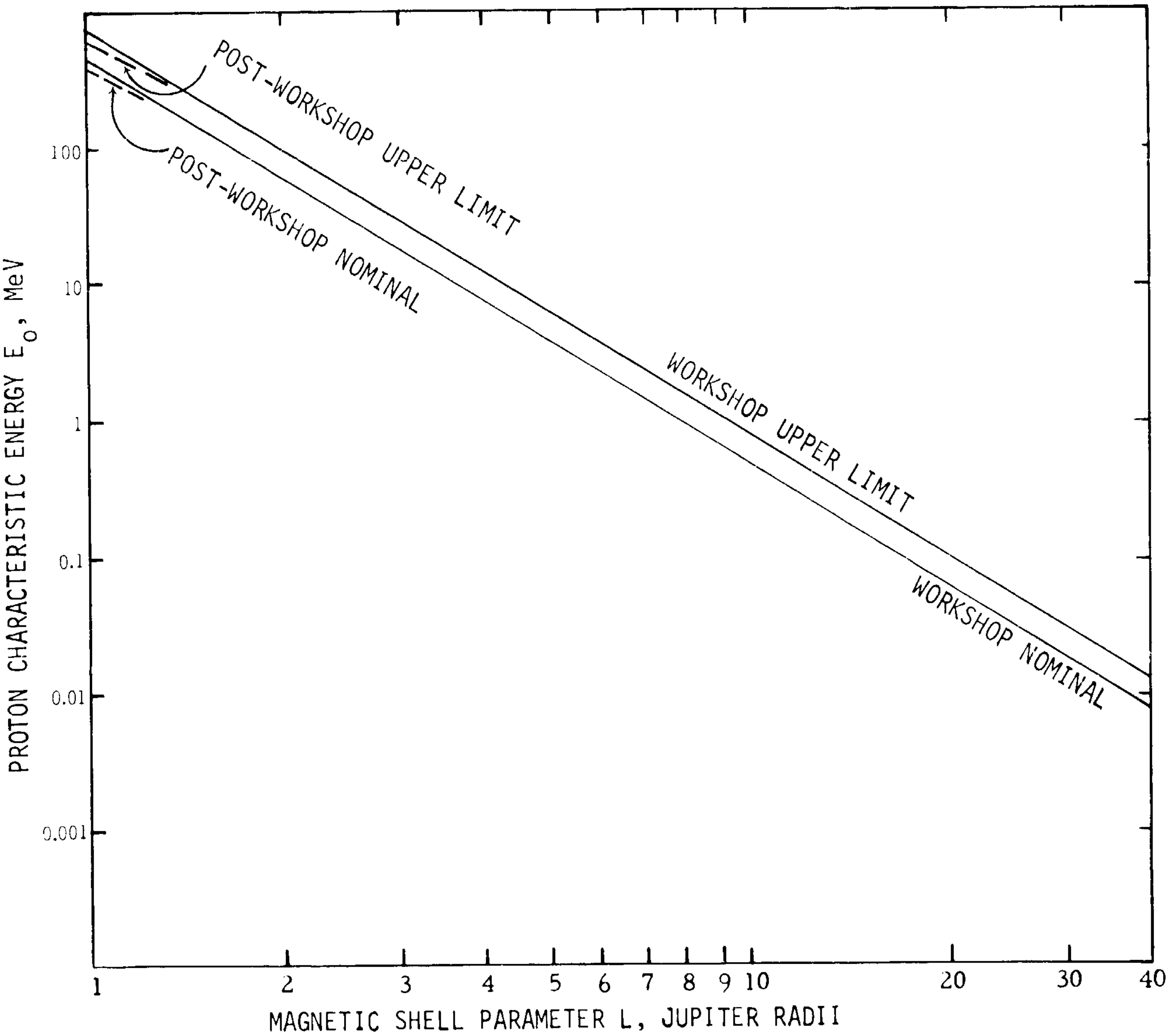

Figure 4. Model proton energies as functions of distance from the dipole in Jupiter's magnetic equatorial plane

Jupiter as severe as those proposed. One question is whether or not a mechanism exists which will produce electron diffusion rates large enough to support the computed synchrotron loss rates. Another question is whether or not the interaction of an energetic proton population with the atmosphere or the satellites would produce observable effects.

In formulating the models, the assumption was made that there are no losses. The concept of satellite shadowing put forth by Hess and Mead provides a significant loss mechanism which could prohibit the radial diffusion of charged particles from the magnetopause into small L values.

Atmospheric scattering could only be effective as a loss mechanism very near the planet because of the relatively small scale height. However, scattering by the plasma is a potential loss mechanism. Thus, the diffusion process should be examined carefully, assuming fluxes on the order of those predicted by ion-cyclotron stability considerations at intermediate L values, calculating the inward diffusion of the protons both assuming and neglecting satellite shadowing, and assuming plasma scattering calculated using Brice's plasma model. This would help to settle the question of flux dependence on the L-shell parameter, especially at small L-values and the magnitude of the flux inside L=2.

Finally, a recommendation was made for the continued inclusion of an adequate experiment complement in future spacecraft missions to define fields and particles near the planets.

FINAL DISCUSSION

DR. VAN ALLEN: In the Earth's proton belts, if you have a theoretical predisposition, you can find L^{-3} over small ranges like from L=3 to L=4.50. But if you come at it in a purely empirical manner (based on observation or experience) you don't get L^{-3}. Different people who have done this don't even get exponential spectra, much less any zeros, so I think there is a very great misrepresentation of the knowledge of the Earth's magnetosphere promulgated by the people who like to think more simply in the theoretical manner. We shouldn't fool ourselves. That does not represent the Earth's situation. The trouble is that the empirical approach has no generalizing quality the way the diffusion people have, because they have a physical principle.

DR. DAVIS: Are there any attempts to explain this discrepancy for the Earth?

DR. VAN ALLEN: I don't think so, not seriously.

DR. KENNEL: I would like to comment that also, in all of these radial diffusion solutions, one thing comes out, and that is that whatever happens beyond Io doesn't really matter. The other side of this is that whatever happens at Io does matter. If you look at the current systems that Goldreich and Lynden-Bell speak about when they are talking about Io, it very much resembles a traveling substorm going around and around the planet, and it generates a copious amount of decametric radiation which, presumably, electrons radiate. If this model is valid, one might expect to find some significant electron acceleration.

DR. DAVIS: Would one component of this be that Io might be able to accelerate electrons very nicely and not be able to do much with protons?

DR. KENNEL: The *high-frequency* radiation suggested is at least interactive with the electrons.

DR. WHITE: Several of us addressed ourselves to the problem of the high-energy protons. Only in the upper limit, I think, did most of us say that we thought that one would have the diffusion going inward toward the planet. Even in the upper limit, there was some question. Only in that case does one have the energy as $1/L^3$. If high-energy protons are put in by some other means, then they could have any distribution which would depend on the source and the losses. In particular, if it is put in like calculations of CRAND process, it would indeed be a different energy distribution and also have a different spectral distribution.

DR. MEAD: Much lower flux, also.

DR. WHITE: That's right.

MR. BECK: Would it be safe to say that we potentially have two sources--one the CRAND source and the other the solar wind source with which we assume L-shell diffusion inward? And that the CRAND source provides the basis for estimating the lower limit proton fluxes--low flux and high energy--while the solar wind source provides the basis for estimating the nominal and upper-limit proton fluxes which are of more moderate energy.

DR. WARWICK: It certainly has to be there.

DR. WHITE: That's right. It is a calculable point.

DR. WARWICK: And it is calculable given the magnetic moment planet.

DR. KENNEL: Maybe we can state the situation as this: For this meeting we are all theorists, and there exist a number of well-posed theoretical techniques for the Earth's magnetosphere: CRAND, radial diffusion in from the boundary, and pitch-angle diffusion. It is our responsibility to clarify what those well-posed techniques would say for Jupiter, and I think that is what this meeting has been all about. On the other hand, I think we should be very, very careful to realize that similar exercises were made for the Earth's magnetosphere before the launch of the first satellite.

DR. BEARD: I wonder if there wouldn't be general agreement that radial diffusion with conservation of the magnetic moment is reasonable to assume. This would imply that characteristic energies depending on L^{-3} make the most reasonable assumption in the presence of a large margin of error.

DR. MEAD: I think that should be qualified. I would say that if we are talking about the possible high proton fluxes, these high fluxes would seem to get in either by some type of diffusion which would (as most of us agree) have to come pretty close to conserving the first invariant and therefore, the high flux protons would almost certainly have very close to L^{-3} dependence. Then if we get down into the lower CRAND fluxes, we can postulate the difference.

MR. BECK: What L-dependence does the spatial distribution of the flux have?

DR. CORONITI: The mu-conserving radial diffusing equation, which the origin would be L^{-3} energy dependence, says that you can't diffuse the flux inward if the flux falls off any faster than L^{-3}. That is the limit, though the density may be different.

DR. BARENGOLTZ: Doesn't that depend on what the L-dependence of the diffusion was?

DR. CORONITI: No; it is independent.

DR. VAN ALLEN: Is that an integral flux or what?

DR. CORONITI: It is the flux at a specific given energy. Speaking of the radial diffusion equation, you have to realize that that is a mu-conserving argument in that it assumes that the distribution function is the function of μ equals the constant. Now, if our picture is right regarding the particles interacting with ion cyclotron turbulence all the way in so that the mu is continuously violated, we don't know what the diffusion coefficient is nor do we know at what power of L one really should scale the flux. This is something we have to solve.

DR. KENNEL: It is an argument in the mu-conserving region.

DR. THORNE: I think the point is, then, as long as you are in a region where the sinks are much slower than the sources and diffusion coefficient is carrying them in faster than you are losing particles, that mu is still essentially conserved. So I think the flux should increase at the maximum rate as L^{-3} up to where the point at which the diffusion starts.

DR. CORONITI: It is a calculation that has to be done. You can't say that.

DR. BARENGOLTZ: Do you have any idea which way you would go if it were violated?

DR. BRICE: Well, the violation of mu tends to precipitate the particles.

DR. KENNEL: You don't lose the particles. You make the distribution isotropic.

DR. BRICE: But the energy of the particles isn't going to be changed all that much.

DR. KENNEL: Not the energy, but the ratio of energy parallel to the perpendicular.

DR. BRICE: That is not going to be changed all that much either, because one component is going up like L^2 and the other like L^3. Thus, a little bit is taken out of one and is put into the other; it is a small factor.

DR. KENNEL: I think the energy argument is fairly good. If you argue only that it will just compress the whole diffusing plasma, the energy would go as L^{-4}--between L^{-4} and L^{-3}.

DR. MEAD: I have to say that that may be true in the outer region of the proton propagation, but if there are any losses, there is nothing that says what the L-dependence is, unless you know exactly what the losses are. I am looking, for example, at the final curve in the Nakada-Mead paper. There is a slope on the radiant side that turns over, has a maximum, and comes back down in. All of it depends on where the losses are and what kind they are. I think perhaps that what we are saying is that in the absence of any losses, if protons diffuse inward (conserving the invariants with no losses of any kind), then the limiting slope on the right-hand side is L^{-3} to L^{-4}.

DR. BRICE: That is probably a good approximation into some distance, but the question is: where is that distance? Suppose you have a wall that absorbs everything at L=2 or something approximating L=2. If the diffusion coefficient went like L^6, then within two-sixths of an L or four-sixths of an L or something not much bigger than that, you would be pretty close to L^{-4}. It is really a question of the power that the diffusion coefficient goes like, in close. If the diffusion coefficient is relatively independent of L and L^{-1}, then you could go either way at the number density for quite a long way out--at least under L of a few magnitudes.

MR. THOMAS: Why doesn't that get rid of the electrons faster than the synchrotron lifetime?

DR. BRICE: Well, if this sort of thing is moving them into the atmosphere, you are going to lose them at an L of 1, and if it goes like L^{-1}, that would be influential inside L=2--not much beyond that.

MR. BECK: In the model Warwick put together for the protons, the number concentration has an L^{-4} dependence.

DR. WARWICK: N goes as L^{-4} in that model.

DR. THORNE: Dr. Warwick's diffusion limit will put a limit of N increasing like L^{-3} or L^{-2}, assuming the energy increases.

MR. BECK: Would it be reasonable to assume that the flux increases at a maximum rate depending on L^{-3}?

DR. KENNEL: That is the fastest increase you could have from the diffusion source.

DR. CORONITI: That is what we used in our numbers this morning. We are giving 10^8 and 10^9 at L=2.

DR. BRICE: It's a little higher than that. Dr. Thorne and I just went through this, trying to separate our discrepancies, because I had a β ratio of radial energy down to 0.1 at L=6 or L=7, and his appeared to be somewhat smaller than that. I think that we have just about straightened out that, and we are pretty much in agreement that a β of 0.1 is at about L=6. There is an uncertainty here in the anisotrophy. In using the anisotrophy of 1, you get a smaller β than if you seem to say the third or something less than 1. The energy of the particle is going to be roughly three times the parallel energy, so there are a couple of factors of about 3 which make about an order of magnitude, so that I think the proton fluxes that Thorne quoted should go up by a factor of about 3 MeV and, say, 3×10^9 at L=2. Other than that, we are in agreement.

DR. MEAD: I think we can say if you are talking about a model that has proton fluxes of 3×10^9 at L=2, then, the fluxes of these protons will fall off as L^{-3}.

DR. BRICE: That's correct.

MR. THOMAS: Is that a fair upper limit?

DR. MEAD: Yes. So if you really want to push the upper limit way up, then you can be very confident that the fluxes will fall off as L^{-3}. I think there are those of us who would not look at nearly such a high upper limit. In this case, there is more uncertainty as to how these fluxes fall off. However, it is wrong to assume an upper limit this high and then fluxes that, because of the uncertainty exponent, fall off as L^{-1} or something like that.

MR. BECK: I have a question about that. Didn't we come to the conclusion earlier that the ion-cyclotron loss model was really an extreme upper limit? Are there not other loss processes, such as electrostatic loss modes, that would bring the fluxes down more?

DR. BRICE: No. We don't have any strong indication that the electrostatic waves would have a major influence. The theory is not very well worked out, but the observations on Earth are that this has a strong influence when β is near 1 with the magnetic energy density and the particle energy density comparable, whereas when the β gets down to 0.1, then the electro magnetic instabilities appear to dominate.

MR. BECK: The question is just how conservative are we being with 3×10^9 proton/cm^2-sec proton fluxes at L=2?

DR. BRICE: I think Dr. Mead's point, if we can make it sort of a synopsis, is that if we have an L^{-3} dependence and we are going up to that L=2 here, and if we are going up to, say, 3×10^9 if we have loss-mechanisms in here, we may have a less rapid L-dependence.

DR. MEAD: I think there are very real number limits that the people this morning talked about that exist at L=6 to 8.

DR. THORNE: I think the limit on the flux at L=7 is going to give you something like a flux of 10^8 as an upper limit.

DR. WARWICK: One point which I made before is: here, there is a strong model-dependence on Neil Brice's model of thermoplasma in the L=5 to L=10 range; although I am not trying to say that I have discovered a new upper limit to density. The one that Brice gives is completely consistent with what I know. However, I would emphasize that that is a theoretical prediction, and it is not something that depends on strong observational data.

DR. BRICE: That's correct. Jim (Dr. Warwick), I think what we need to do is to say let's arbitrarily reduce all of those densities by the same order of magnitude.

DR. WARWICK: Why not 2 orders of magnitude? What would 2 orders of magnitude do?

DR. BRICE: If we reduce it 1 order of magnitude, the affect of that is simplygoing to be to move out the crossover point at which the strong diffusion no longer becomes applicable so that instead of precipitating my first invariant violation into an L of 6, it would quit at an L of 8 or 9 or something like that, because there is sort of a basic L^3 factor in there. The critical energy is B^2/N and B^2 is going like L^6, whereas the energy of the particle is going like L^3. So that L^3 factor means that all you are going to do is to move out the point at which you simply have limiting fluxes. We should do that--just move that barrier out to--instead of L=6, to L=9 or L=1--and see what it does to the β and to the fluxes.

DR. WARWICK: We shouldn't lock ourselves in on that model yet, although it may be right.

DR. BRICE: But the critical point is that as long as the density is high enough so that your energy threshold is less than the particle energy, then the flux that you calculate is independent of this number density. That is a very important point. What we are arguing about is having the number density large enough in order that the threshold is small enough so that the pitch-angle diffusion is effective. Once we are <u>above</u> that threshold, then there are no uncertainties, and the number densities really don't change at all.

DR. THORNE: I think that what you are saying is that these turbulent estimates are somewhat conservative in the sense that if the densities are very, very low, the particles wouldn't be unstable at all; so, if anything, they should penetrate across the boundary at the magnetopause. The particles would just end up increasing like L^{-3} all the way in, which would result in the largest fluxes.

DR. BRICE: If we increase it by 10^2 then all that says is that the threshold for this effect is way less than the particle energy. That really doesn't change the flux.

DR. BEARD: Isn't the purpose of this discussion to come to some agreement on what seems to be the most reasonable value to choose?

MR. BECK: Dr. Brice, as I recall (in the paper that you gave), you had numbers that looked like Warwick's numbers for protons. Is that correct?

DR. BRICE: I think that when we go through the diffusion calculation, as I did, I think I am in total agreement within a factor of 2 or something, which is surprisingly good, with Kennel and Thorne. On the other hand, we are hard up against the fact--and I think it is a fact--that the electron fluxes that we would calculate by the same process as somewhat higher than the electron fluxes observed or deduced from the decimetric radiation. This really makes one question: how much confidence do you place in this upper limit? What we would like to do is to remove the discrepancy between the theoretically expected values for the electron fluxes and what we deduce from the measurements. If we can do that, it will give us considerably more confidence in the theory and an excellent increase in the confidence of Jim's theory. Dr. Thorne, what number do you get for the electrons? Do you get the same number for the flux? Is the flux the same or the density the same?

DR. THORNE: Flux is the same; and I think that there is one other point to be made about the electrons. That is that they are liable to be unstable to submit their losses over a much larger range than the protons. If we are going to scale the stably trapped fluxes in from the outer-most boundary where you are most apt to see significant losses, you may be somewhat lower.

DR. BRICE: If we summarize this, we have 1) an upper limit for the protons and, 2) an upper limit for the electrons; but we don't know what confidence level to assign to them this afternoon. There are some additional factors that need to be taken into account that represent perhaps two or three days' work on this, which normally takes two or three weeks to do.

DR. MEAD: I think you people are entirely too willing to assume that the upper limit calculation here is going to be equivalent to the most likely or nominal environment. I guess Dr. Hess and I would say that certainly we would have to go along pretty well with most of the things you people are saying about upper limits. If we were to answer the question, we would say that the nominal or most likely environment is far lower than this. There may be other factors that would exist with the protons that would make their most likely value a lot less than these upper limits. We have always been talking about upper limits all the way through here.

DR. THORNE: Could we make a counter argument against that by referring back to the Earth's radiation belts where it is known that provided you are in the *regime* where the theory works, provided the energies of the protons are above this critical value for instability, we know that the protons there obey the stably trapped flux limit, and they seem to sit at that limit. They don't deviate, and this is the important point. This upper limit is probably a limit in which the proton belts are populated.

DR. BRICE: The whole question, really, is bringing the electron upper limit close to the observations. When the upper limit gets close to the observed values, then I think we are in pretty good shape. I think the other thing we need to do is to look at the satellite shadowing. Let's assume that the satellites are perfect conductors and see what they do to the protons. It is clear that the electrons may get around to satellites and the protons <u>may</u> not.

DR. WARWICK: Or vice versa!

DR. BRICE: No; because the protons have a much bigger lambda range.

DR. WARWICK: I know, but that may not be the only thing that is involved.

DR. THORNE: I think that maybe we ought to discuss the various problems of radial diffusion, because that seems to be a hanging-up point. There are several models that are being proposed. Dr. Brice's model will work very well at low L-values. Electric field diffusion has a smaller rate for L. It seems to be adequately getting particles past the satellite Io--probably not much farther in than that.

DR. BRICE: The plasma radiance will bring them into Io with an L^{-2} or something like that.

DR. MEAD: Bring in what? Protons and electrons?

DR. BRICE: Yes. Just at flux-tube interchange, all the way from Io to the solar wind.

DR. THORNE: That way is easy, though. I think any sort of diffusion model will bring you in from the outer regions.

DR. BRICE: From Io on in is the "hooker;" that's correct. I think it would be useful to do some calculations there based perhaps on difference in rotation periods for the magnetic field in the neutral atmosphere for the differential rotation from the radiant pole. I think it is very clear that the diffusion in the inner region, even given that it is driven by the ionosphere, needs to be quantified, because it is a pretty thin "hand-waving" kind of argument right now, which we have accepted rather liberally just because we see the electrons in there.

DR. WHITE: I would like to suggest that the electric field diffusions will get them in much farther than Io. In fact, I will be glad to talk about getting them in almost to 2 at the appropriate time.

MR. BECK: In bounding this proton flux problem, apparently we have something that is converging to be a very good upper limit now.

DR. MEAD: The best upper limit right now seems to be for protons around 3×10^9 at L=2 and falling off with L^{-3}. Most everyone seems to feel that it is pretty unlikely you will find fluxes very much higher than that.

MR. BECK: What can we say about a nominal model? What is the greatest lower bound?

DR. BRICE: We equate the proton and electron densities, not the fluxes. If you take the proton density and say it is the same as the electron density and give the protons, say, five times more energy, then we have got a difference of a factor of 2. I think that is probably the best nominal.

DR. KENNEL: Would you call that nominal in the sense that it is probable, or is that just a reasonable middle range estimate? I mean you have to be careful, because engineers use nominal as expectant. The low range is obviously zero.

DR. BRICE: We have two uncertainties in the electrons now. One is the relativistic effects on the electrons, which we really don't know about; the other one is in the interpretation of the observations. Now, if we say that the proton number densities are like the electron number densities, then the energies may be five times higher. If we eliminate that uncertainty by just trying the protons to the electrons, then if you want to say a factor of 10 (instead of 5) you would probably cover most of the points of the other problem. For a nominal value or expected value, I would say the same densities as the electrons and 10 times the energy, which probably is a little on the light side.

DR. MEAD: If I look at these curves properly, the nominal model varies from the upper limit that we are talking about by something like 2 to 3 orders of magnitude.

DR. DIVINE: Three orders of magnitude at L=2.

MR. BECK: Then, we have general agreement to take the Warwick model as a nominal value, and increase the energy by about a factor of 10.

DR. BRICE: That means that we have got to set Jim's number for the electrons, too. There is a question that we haven't answered about lowering the electrons.

DR. WARWICK: I can't say anything very profound about that. I feel very confident of that, as I have indicated already. I think that the right way to get it is to assume that you know the magnetic field strength, take the best brightness distribution that you think you have got, and to compute on the basis of the intensity, not the total flux, but the intensity. I have done all those things, and I came up with the numbers that are shown.

DR. BRICE: Jim (Dr. Warwick), did you do the same thing as Dr. Berge?

DR. WARWICK: I did make a comparison of Glenn Berge's data, and it looks consistent with that. We are talking about a very difficult problem. We are talking about something that has many styles of approach and as much uncertainty as the proton numbers (which are a theoretical complication), but this has not as much uncertainty in the sense that we are seeing something, rather, numerically, perhaps it has many uncertain factors. Maybe we ought to have a workshop on interpretation of synchrotron emission.

MR. THOMAS: If you wanted to put on an upper limit for the electrons like we put on an upper limit for protons, perhaps you could assume that the upper limit electron flux is 100 times the nominal electron flux.

DR. WARWICK: Not 100 times! Maybe 10 times, but I don't really like that. Maybe even 10 times is overly generous. I think 3 times the factor is the uncertainty that Neil Divine put on the number when he designed the criterion monograph, wasn't it, Neil?

DR. DIVINE: I applied 3 times the factor in two places.

DR. WARWICK: He applied the 3 twice and came up with 10.

DR. BEARD: What was the energy you assumed?

DR. DIVINE: 6 MeV.

DR. WARWICK: The numbers that I used were 6 MeV at the peak of the belts at a flux of 2×10^7 electrons/cm^2-sec.

DR. GULKIS: Also, that is the same that we calculate by an entirely different technique. You calculated yours (Warwick's) on the basis of brightness. We calculated ours on the basis of total flux, and they do agree within a factor of 2 or 3. But I think that probably is because you really took into account the beaming, whereas our calculation doesn't.

DR. VAN ALLEN: One thing to note on Jim Warwick's model is that he does have the concentration falling off as L^{-4}, which the theorists won't stand still for, so that should be perhaps discussed separately.

DR. THORNE: The point there is that you are violating mu in the synchrotron emission.

DR. BRICE: You really do not see much synchrotron emission from L=2 on out.

MR. BECK: Suppose that we take the Warwick model for the nominal electron model with 2×10^7 electron/cm^2-sec at L=2 and let it fall off as L^{-3}. Is that the consensus model?

DR. MEAD: When you say a flux of 2×10^7, is this representing a specific energy?

DR. WARWICK: That is a 6-MeV electron (at peak).

DR. MEAD: To answer your question, we are using his interpretation that defines energy as well at the peak--namely, 6 MeV.

DR. WARWICK: Right.

DR. VAN ALLEN: Is this a two-parameter curve? Do you have flux vs L? Are both things changing simultaneously? Are you representing the total number greater than zero energy because the spectra is changing? Thus, am I to understand that it is not the number of particles of energy greater than the critical energy? It could be a number greater than zero energy, because with an exponential spectrum it is only a factor of 2 different.

DR. WARWICK: That would be the correct sense in which to infer it. In fact, I have been pressed to say just what the spectrum was. I will say what I thought the spectrum was, although at that time, people had said the spectrum was E^{-1} differential.

DR. VAN ALLEN: When the experimentalist calls it flux versus anything, he usually means the flux greater than some specified fixed energy.

DR. BRICE: Your number is essentially a mono-energetic flux.

DR. WARWICK: That is correct. That is all we know about E_0.

MR. BECK: Was the spectrum not chosen in such a way that it was very peaked?

DR. BEARD: I think Jim Warwick and I would agree to be in total disagreement on this. I can't get any comparison by wiggling the curves up and down and adjusting the parameters that don't produce electron energies more like 30 or 40 MeV.

DR. BRICE: Dr. Warwick's magnetic field may be a little high.

DR. WARWICK: Not an ounce.

DR. BEARD: Actually, I used 10 gauss in mine.

DR. WARWICK: That I won't budge on. We could go on a long time about that. But, really, I think the point here is that the synchrotron data simply convolves too many parameters for us to talk about meaningfully beyond a certain point. Anyone can make this list, but four or five or six things all fold together. How we are going to sort them out is not something that is easy to do.

DR. BRICE: Dr. Warwick, there is one point that I think ought to be brought up about this, and that is about your flux value. This essentially assumes a rather sharply peaked distribution, or this flux is reasonable for a sharply peaked distribution or a Maxwellian distribution. The distributions that we see in the energetic particles tend to be rather more flat than the Maxwellian. The Maxwellian distribution is falling off awfully, awfully quickly, particularly on the high-energy end and I think probably doesn't become constant as rapidly. So, I think it would be useful to consider a rather more flat flux vs energy distribution. Would that increase the flux or would it decrease it?

DR. BEARD: There is one caution on that, though, and that is at the high-energy end--if you are going to make it flatter than Maxwellian, the higher energy end loses its energy not in a year, but maybe in seconds!

DR. LUTHEY: The trouble with his power law is that beyond something like 15 MeV, you are supposed to lose electrons by radiation loss, and it doesn't show up like that.

DR. DIVINE: The normalization in power law spectrum is quite sensitive to cutoff.

DR. LUTHEY: That's right; and you can only compute the cutoff by an approximation. I assume that the power comes primarily at the peak of the power emission for a single electron.

DR. VAN ALLEN: Is the latitude dependency a significant topic of discussion? It is conceivable to phase the approach for the encounter such that the dipoles sort of tilted down, you then can sort of sneak through when the hat is tipped, so to speak. If it is a narrow latitude distribution, it might be a factor of 5, available in this category or point of view. The equatorial distribution is altogether here, I think, and it depends on the equatorial pitch-angle distribution, how tight it is in latitude.

DR. THORNE: But the encounter time is several corotation periods, so you are always going to go through the magnetic equator.

DR. VAN ALLEN: No; not at the worst place. I mean, if you really want to work this as an engineering problem, you can get a factor of 5.

DR. BRICE: Depending on how sharply confined it is.

DR. MEAD: Are the expected distributions to be so sharply peaked they will be down by a factor of 5 in 10 degrees off the equator?

DR. THORNE: Dr. Coroniti made that argument yesterday. He said that 75% is located within 10 degrees.

DR. BRICE: That isn't the point. You say 75% is located within 10 degrees, but what is the flux 10 degrees up from--the equator?

MR. BECK: In this specific model, the E-folding value is about 30 degrees.

DR. MEAD: That is not going to help much.

MR. BECK: Is there any feeling about the latitude dependence that is different from the statement that we have in the model, namely that it E-folds at 30 degrees?

DR. KENNEL: The radial diffusion models alone, without any pitch-angle scattering, would suggest that the anistropy increases by L, so that if you had isotropic fluxes far out, you would get anistropies on the order of 25 for the maximum of the belt (which is much flatter than what you have seen from the electrons). If you assume they diffuse in and are isotropic--to say L equals something--then you get anisotropies like 3 at L=2.

DR. THORNE: Doesn't the synchrotron data give you information on the isotropic pitch-angle distribution?

DR. WARWICK: Yes. That is where this 30-degree number came from--from the beaming of the synchrotron emission.

MR. BECK: Now that we have a nominal electron model, can we base the nominal proton model on the nominal electron model. Our nominal proton model has the same number density at 10 times the energy as the electron model.

DR. BRICE: It is the same number as 10 times the energy density at L=2, assuming that the flux goes as L^{-3} and the energy for the proton goes as L^{-3}.

MR. BECK: Same number of 10 times the energy density? How does that agree with Warwick's model?

DR. DIVINE: It is not very different--perhaps a factor of 3.

DR. BRICE: It is not very different, unless you come inside L=2, i.e., if you come into L=1.50 or even L=1.05.

DR. MEAD: That is a point. Does it not flatten out?

DR. DAVIS: Our theory is that there isn't enough diffusion at the top of the atmosphere, so it must flatten out somewhere.

DR. MEAD: I agree.

DR. DAVIS: Where is that likely to be?

DR. THORNE: On the Earth, the velocities are very close, as L=1.25. Around Jupiter, the upper atmosphere is thin.

DR. BRICE: But that assumes that you have a diffusion which is very strongly L-dependent, or that it assumes a CRAND source that is essentially in that region.

DR. SMITH: One way of saying it is that it isn't going to flatten out at foreseeable distances which spacecraft are going to be. If somebody is really going to get down and skim through the atmosphere, then you are going to have to reconsider this.

DR. MEAD: Dr. White, where is the peak of the Earth's protons at L?

DR. WHITE: At 100 MeV (that is at about L=1.4).

DR. MEAD: It seems to me that if you get much in past L=1.4, first of all, you would have an offset dipole that is going to start wiping out. Secondly, you have to stay very close to the 90-degree pitch angle. Otherwise, they are going to bounce up and down in the atmosphere. It is very hard for me to see how you can continue to go up in flux at any planet much inside past about L=1.4

DR. WHITE: But it is the atmosphere, Gil (Mr. Mead), that is cutting the belt off in the case of the Earth, and we are all saying that there is no atmosphere in the case of Jupiter. There is an atmosphere of about 10^4/cm at the middle of the belt. It is neutral.

DR. BEARD: Jupiter's atmosphere is probably something like one one-hundredth of what it is on Earth.

DR. MEAD: Cooling the action of the electron is not going to do anything. Is that what you are saying?

DR. BRICE: We are saying we get a lot more atmosphere at L=1.4.

DR. WHITE: So there are only two things that I can see to cut it off: 1) run into Jupiter, and 2) don't put any protons on the outside.

DR. WHITE: If you are talking about a nominal, there are many considerations. Now if you accept the model that you are using for the upper limit, then what you say is true. If you don't accept that model, then you get an entirely different answer, so it is very model-dependent.

DR. MEAD: Would you say that it is a nominal case?

DR. WHITE: If you ask Dr. Hess, he will put it down by 4 orders of magnitude from what you are talking about.

DR. BRICE: Is it worth arguing about--whether we are going to flatten this from L=1.1 or keep it going, because at an L from 1.3 to 1.1 won't change it very much.

DR. SMITH: Is it possible that it flattens at L-2 or something significant, farther out? I judge from the consensus here that that is not true, but it is close to the spacecraft or likely to go and spend its time. It is not flat.

DR. WHITE: If we are talking about a nominal, then I don't think everybody at the table here is anywhere near agreement on that estimate; that the nominal is going to be the upper limit until you get into L=2. It is dependent upon a model. If you want to call it still an upper limit, fine. We agree to that.

DR. DAVIS: If you put in a flux something like the nominal, it is not all clear that the small scale of Jupiter's magnetic field doesn't have a nominal red spot. That is going to mean the surface is irrelevant. That is probably going to flatten it out.

DR. MEAD: In fact, good evidence from the nature of the synchrotron emission at even L=2 is that there are irregularities in the non-dipolar aspects of the magnetic field.

DR. WARWICK: I would express very strongly that everyone who looked at decametric emission took it precisely that way, so if you will accept that qualification, I think that Dr. Davis' point is very well taken.

DR. MEAD: What other parameters are left?

MR. BECK: We need an upper limit electron model that is reasonable--one with an upper bound which is lower.

DR. DIVINE: You can upper bound your electron model by the uncertainties in the unfolding of the synchrotron radiation.

MR. BECK: What is that a factor of? Is it five, maybe?

DR. BRICE: Sam (Dr. Gulkis) said three. How much bigger is the absolute upper bound on the electron of the flux?

DR. WARWICK: The dipole moment is about 4×10^{30}. A center dipole at the equator with a moment of 4×10^{30} is 12 gauss.

DR. GULKIS: But your magnetic field value is slightly outside the value determined by the circular polarizations. I think your estimate is somewhat dependent upon the model that you assumed for the decametric emission. I think that the uncertainty might be taken to be your estimate and the circular polarization estimates.

DR. BRICE: There is enough uncertainty to say that the decametric might be the cyclotron frequency, which would bring it down to 8 gauss.

DR. WARWICK: That is not consistent with the phenomenology of decametric emission, despite what Goldreich and Lynden-Bell have said; and despite what my colleague, Sam Gulkis said.

DR. GULKIS: If you heard the statement that Dr. Davis made, there might be anomalies producing the asymmetries in the magnetic field rather than the displaced dipole.

DR. WARWICK: I don't believe that that is the case, however, the point he was making, that is correct. In the model I have proposed, there are decentering effects which might play the same role as any possible anomalies that someone else might describe, so, putting all those things together, I say it is reasonable to talk about these as anomalies, but if you are going to talk about the asymmetry of decimetric emission, you begin to set bounds on what the nature of those anomalies are. If you are going to talk about the rotation of decametric emission, you begin to set boundaries on the nature of the anomalies.

DR. GULKIS: I am slightly more pessimistic than you are. Certainly, polarization measurements should be taken into account, and they suggest a slightly lower value.

DR. WARWICK: Thirty percent, as Neil Brice says, may be so.

DR. BRICE: The other thing we have to be worried about is whether we have a flattened distribution and not a peaked distribution, and that might up the fluxes.

DR. DIVINE: There are two things which I did in creating the upper-limit model that I have been working on so far--take Warwick's nominal model and apply an uncertainty to both the energy parameter and the flux parameter (a factor of 3). Now, this is not to say that the upper-limit model of this variety would describe the electron population everywhere, because then, of course, it gives you too much synchrotron intensity. On the other hand, if the synchrotron source were narrower in L, as it might be, then the nominal model flux would have to be pushed up. This is what that upper-limit model is attempting to envelope.

DR. BRICE: Are you saying you want to be higher than the electron flux everywhere?

DR. DIVINE: Intended to be an "upper limit" at that sense of the point.

DR. GULKIS: Your limits certainly seem reasonable to me.

DR. DIVINE: Except that we were arguing yesterday afternoon in a smaller session, that in the absence of physical reasons, the dependence of the energy and flux on L beyond the peak should be the same in a nominal model as in the upper-limit model.

DR. GULKIS: You were taking a larger error as you went out.

DR. DIVINE: That's correct. And as we were discussing in the smaller session yesterday, some people felt that that was being overly conservative.

MR. BECK: Shall we look at the models we have constructed? Will you describe them, Neil?

DR. DIVINE: The nominal model here having L^{-3} dependence in the flux, a number concentration at L=2 (approximately the same as the electrons) and energy up by a factor of 10. The upper-limit model essentially has 3×10^9 at L=2, with 100 MeV. L^{-3} dependence is in both the energy and the flux.

MR. BECK: And everywhere inside of L=7 or so, the flux exceeds that given by the preworkshop upper-limit model. That model was rather severe from the radiation-effects standpoint.

DR. KENNEL: Is that the L^{-3} dependence?

DR. DIVINE: Yes, it is.

DR. VAN ALLEN: What is your nominal value at L=2? Is that 7×10^6?

DR. DIVINE: Well, the rationale is to use the number concentration the same, but they have increased the energy, so just where it would fall, would require a couple of minutes for computation. I suspect it is a little higher than the old nominal, but not much.

MR. BECK: The question was what is the effect of the upper-limid model relative to the upper-limit model that we have already had.

DR. DAVIS: This current upper limit that we have doesn't go out to $\beta=1$ at that end, because of the energy.

DR. KENNEL: May I see if you can get an agreement from Neil Divine on this--that this is an upper-limit model. Would you be willing to shave the numbers a little bit down (because I don't see any way of getting the upper-limit model out of the danger zone down to the spacecraft)? I think that is a fair estimate. We can't get the upper-limit model down to where it presents no danger to the spacecraft. I think that is about all you can conclude from this.

DR. DAVIS: Essentially, it is an upper limit based on one model which we understand reasonably well but aren't at varying degrees of assurance as to how relevant it may turn out to be.

DR. KENNEL: For that model, we cannot get down to a safe level.

DR. WARWICK: And the basic parameter of the model that produces this effect is the large magnetic field of Jupiter, which if it is inescapable, suggests that there is a strength in that model. I mean, you can't do away with that feeling, is what I am trying to say.

DR. SMITH: Well, the way to treat that upper line clearly is, is it possible on some grounds that the flux would be that high. I judge from the consensus that it is possible.

DR. BRICE: Close to it. And I don't think we would argue that fact.

DR. SCARF: There is more to it than just the magnetic field of Jupiter. Isn't it true that you are making an assumption about the way that the electrons are normalizing, and your concepts to it, and assuming that the same plasma physics occur?

DR. WARWICK: Right. And we see the electrons.

DR. THORNE: Would these electron fluxes be hazardous?

DR. DIVINE: Yes, but not considerably so.

MR. BECK: Probably interference, mainly.

DR. DIVINE: Some kinds of electronic components like MOS-FETs (metal oxide semiconductor field effect transistor) may have to be avoided.

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APPENDIX A

List of Attendees

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LIST OF ATTENDEES

(*indicates those who presented a paper included in these proceedings)

Axford, W. Ian
University of California at San Diego

Barengoltz, Jack B.*
Jet Propulsion Laboratory

Beard, David B.*
University of Kansas

Beck, Andrew J.*
Jet Propulsion Laboratory

Berge, Glenn L.*
California Institute of Technology

Brice, Neil*
National Science Foundation

Carr, Thomas D.*
University of Florida

Coroniti, Ferdinand V.*
University of California at Los Angeles

Davis, Leverett, Jr.
California Institute of Technology

Divine, Neil*
Jet Propulsion Laboratory

Divita, Edward L.*
Jet Propulsion Laboratory

Gulkis, Samuel*
Jet Propulsion Laboratory

Haffner, James W.*
North American Rockwell Corporation

Hess, Wilmot N.
National Oceangraphic and Atmospheric Administration

Kennel, Charles F.*
University of California at Los Angeles

Klopp, David A.*
IIT Research Institute

Liemohn, Harold B.*
Boeing Scientific Research Laboratories

Luthey, Joe L.*
University of Iowa

Mead, Gilbert D.*
Goddard Space Flight Center

Mihalov, John D.*
Ames Research Center

Neubauer, Fritz*
Goddard Space Flight Center

Parker, Richard H.*
Jet Propulsion Laboratory

Scarf, Frederick L.
TRW Inc., Los Angeles, California

Smith, Edward J.
Jet Propulsion Laboratory

Thomas, John R.*
The Boeing Company

Thorne, Richard M.*
University of California at Los Angeles

Trainor, James H.*
Goddard Space Flight Center

Van Allen, James A.*
University of Iowa

Warwick, James W.*
University of Colorado

White, Stephen
University of California at Riverside

APPENDIX B
POST-WORKSHOP MODELS

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APPENDIX B

COMMENTS ON MODELS OF THE JOVIAN RADIATION BELTS

Leverett Davis, Jr.*

General Comments

The JPL Workshop on the Jupiter Radiation Belt in July, 1971, provided a careful review of the various phenomena that might be involved and a thorough examination of a variety of models that have been considered. The bases selected for the Workshop nominal and upper limit models probably represent the most widely acceptable consensus that could be reached at the present time. However, the numerically quantified models that were accepted as derived from these bases do not, in fact, follow from them in a logically consistent manner. Presented below are revised models including relativistic effects whose derivations from the Workshop bases are more nearly, but not completely, sound. An alternative nominal model is also suggested that does not appear to be significantly less probable than the Workshop nominal model.

Several equally good nominal Jupiter radiation belt models could have been proposed. Consequently, any model must be adequately qualified to identify the individual model and to emphasize the current uncertainty in the description of the Jupiter radiation belt. Models based on current knowledge (indeed, on any knowledge that we may hope to get before the first spacecraft reaches the Jovian magnetosphere) are uncertain by orders of magnitude. If the models are applied to evaluate radiation effects on spacecraft for future missions, the model qualifications should be clearly recognized and should be carried over to qualify results derived using the models.

A desirable goal is to minimize the impact of the Jovian radiation environment on the design of spacecraft for future missions. One possible way to accomplish this goal is to include all reasonable provisions to avoid failures due to radiation damage but not to push this requirement to the point where the possible accomplishments of the mission are substantially

* *California Institute of Technology, Pasadena, California 91109*

reduced. Then, when direct observations of the radiation belts become available, re-target the missions and shift launch dates where necessary so that the radiation design limits are not exceeded.

The Workshop Nominal Model

The bases adopted by the Workshop for its nominal model are, essentially, that:

1) The magnetic field at the equator is 10 gauss and is mainly due to a centered dipole.

2) The flux and energy of the electrons at L=2 can be determined from the observed synchrotron radiation and are 2×10^7 $cm^{-2}sec^{-1}$ and 6.2 MeV, respectively.

3) The energetic electrons and protons originate in the solar wind and reach the inner magnetosphere by an L-shell diffusion process in which the first and second adiabatic invariants are conserved.

4) For all L>2, the number density of protons is the same as that of electrons and the characteristic energy of the protons is ten times that of the electrons.

5) There are no losses of electrons or protons in the diffusion process due to Jovian satellites, thermal gas and plasma, or atmosphere near the surface. Losses at the surface were judged to affect the flux significantly only for L≤1.5.

The basis for item 4, above, is that this is the situation in the solar wind; and for nonrelativistic particles, the relation between the energies, densities, and fluxes of electrons and protons would not vary with L. In the Workshop model, the flux of electrons at L=2 was taken to be three times that of the protons because, with the energies assumed and allowing for relativity, the velocity of the electrons was three times that of the protons.

Other than this, no allowance was made for relativistic effects and it was assumed that L-shell diffusion required the fluxes and the kinetic energies to vary as L^{-3}.

The calculations made at the Workshop to connect these basic assumptions (a valid decision of the Workshop) with curves showing fluxes and energies as functions of L were extemporaneous and different parts were carried out by different members of the group. It is, thus, not surprising that the calculations were not done in a completely consistent way. It is not claimed that the discussion to follow is completely rigorous, but the curves derived should be more nearly consistent with the assumptions than were the previous curves.

There are three basic changes in the procedure.

The first is that the comparison between protons and electrons is made at large L, where both are nonrelativistic and the solar wind ratios should apply, instead of at L=2. The energy and flux curves for electrons are found as a function of L out to L=40 from the assumed values at L=2. The proton energy at L=40 is taken to be ten times that of the electrons, the proton density is the same, and the proton flux is lower by the velocity ratio, which is $(10/1836)^{1/2} = 0.0738$. With this as a starting value, the proton curves are calculated to L=1.

The second is to use the relativistic connection between kinetic energy, E, and L, which is found as follows. If p is the momentum and m_0 the rest mass of the particle considered,

$$(p/m_0c)^2 + 1 = \left[(E/m_0c^2) + 1\right]^2 \qquad (1)$$

Then, p^2 is assumed to be proportional to B and hence to L^{-3}. This is precisely valid for particles that mirror in the equatorial plane. The p^2 of particles that mirror away from the equatorial plane varies somewhat less rapidly with L, but for most of the particles in an isotropic distribution, the discrepancy is very small.

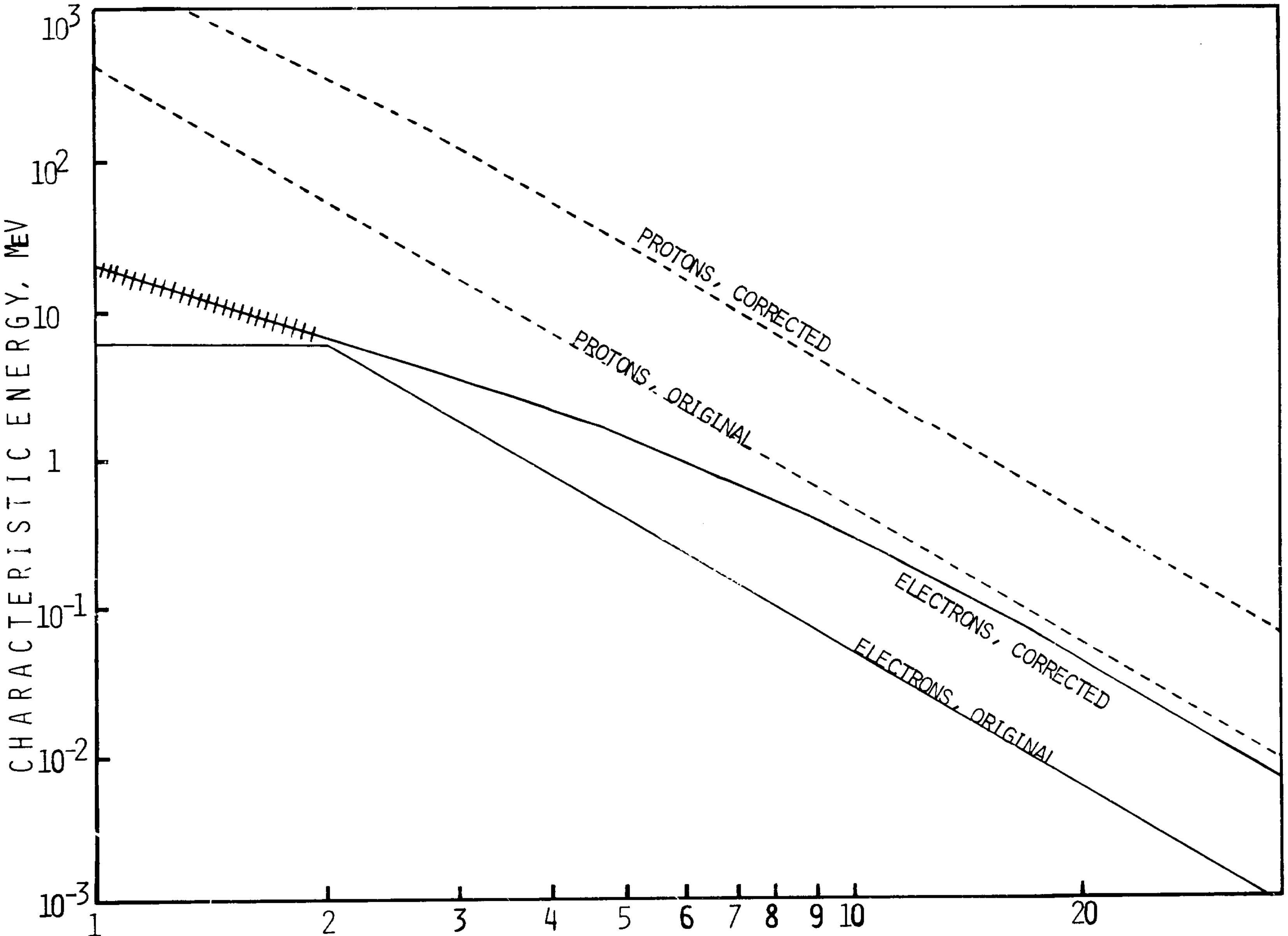

Figure 1. Nominal Workshop Models for Particle Energy vs L

The effect of these relativistic corrections on the variation of energy with L is shown in Figure 1. Note that except at the base point for electrons at L=2, the corrected energies are everywhere larger than the original values. The hatched portion of the corrected electron energy curve, positioned between L=1 and L=2, is calculated in the same way as the rest of the corrected energy curve. Actually, some allowance should be made for the losses due to synchrotron radiation; if desired, this may be schematically indicated by taking the curve to be horizontal in this interval.

The third basic change in the procedure is to determine the dependence of flux on L from Liouville's theorem. Thus, when a population of particles undergoes L-shell diffusion without losses, F (the flux per-unit-energy and per-unit-solid angle) varies as p^2; i.e., essentially as L^{-3}. The total flux, Φ, considered by the Workshop is

$$\Phi = \iint F d\Omega dE \ \mathrm{cm}^{-2}\mathrm{sec}^{-1} \tag{2}$$

For L>2, and perhaps even L>1.5, the assumption that the solid angle involved is 4π involves an error that appears to be negligible for our purposes. To simplify the effect of the energy spectrum, assume that all particles that contribute significantly to the flux of interest are in a narrow band of energy of width dE, centered at the characteristic energy, E. Then, setting $d\Omega = 4\pi$, the integrals may be dropped from eq. 2. The range of E will correspond to a range of p^2 which may be found from eq. 1 to be given by

$$dE = \frac{1}{2m_0}\left[\left(\frac{p}{m_0 c}\right)^2 + 1\right]^{-\frac{1}{2}} d(p^2) \tag{3}$$

When L changes, both p^2 and $d(p^2)$ are approximately proportional to L^{-3} (as discussed above). Thus, the variation of Φ with L contains a factor L^{-3} because of the variation of F, a factor $[(p/m_0 c)^2 + 1]^{-\frac{1}{2}}$ [because of the conversion from dE to $d(p^2)$] and another factor L^{-3} because of the variation of $d(p^2)$ with L.

If Φ, p, and E are the total flux, momentum and kinetic energy at L, and Φ_0, p_0, and E_0 are the corresponding quantities at L_0, we have

$$p^2 \doteq p_0^2(L_0/L)^3$$

$$\Phi \doteq \Phi_0(L_0/L)^6 \left[(E_0/m_0c^2) + 1\right] \left[(E/m_0c^2) + 1\right]^{-1}$$

$$\doteq \Phi_0(L_0/L)^6 \left[(p_0/m_0c)^2 + 1\right]^{\frac{1}{2}} \left[(p_0/m_0c)^2(L_0/L)^3 + 1\right]^{-\frac{1}{2}} \qquad (4)$$

Figure 2 shows the dependence of proton and electron flux with L both for the original Workshop model and corrected by using eq. 4. The hatched section of the corrected electron flux, the section between L=1 and L=2, has been computed using eq. 4. But what should be done to allow for synchrotron radiation losses and losses in the atmosphere is not at all clear; the use of a horizontal section as in the original model probably somewhat underestimates the flux. Note that out to about L=2.7 the proton flux is higher than in the original version, but is lower beyond this point.

Possible Alternative Nominal Models

The Workshop nominal model treated above has many attractive features which resulted in its being adopted as the consensus of the group. It is based on a small number of simple assumptions. It is unlikely that any other single model could be proposed that would be supported with substantial confidence by more experts on the subject. But the Workshop nominal model does have a number of weak points. I think that a better impression of the actual situation could be given if several nominal models were presented and if it was then stated that no model seems substantially more probable than another. One such alternative model is presented below after a brief consideration of some of the deficiencies of the Workshop model.

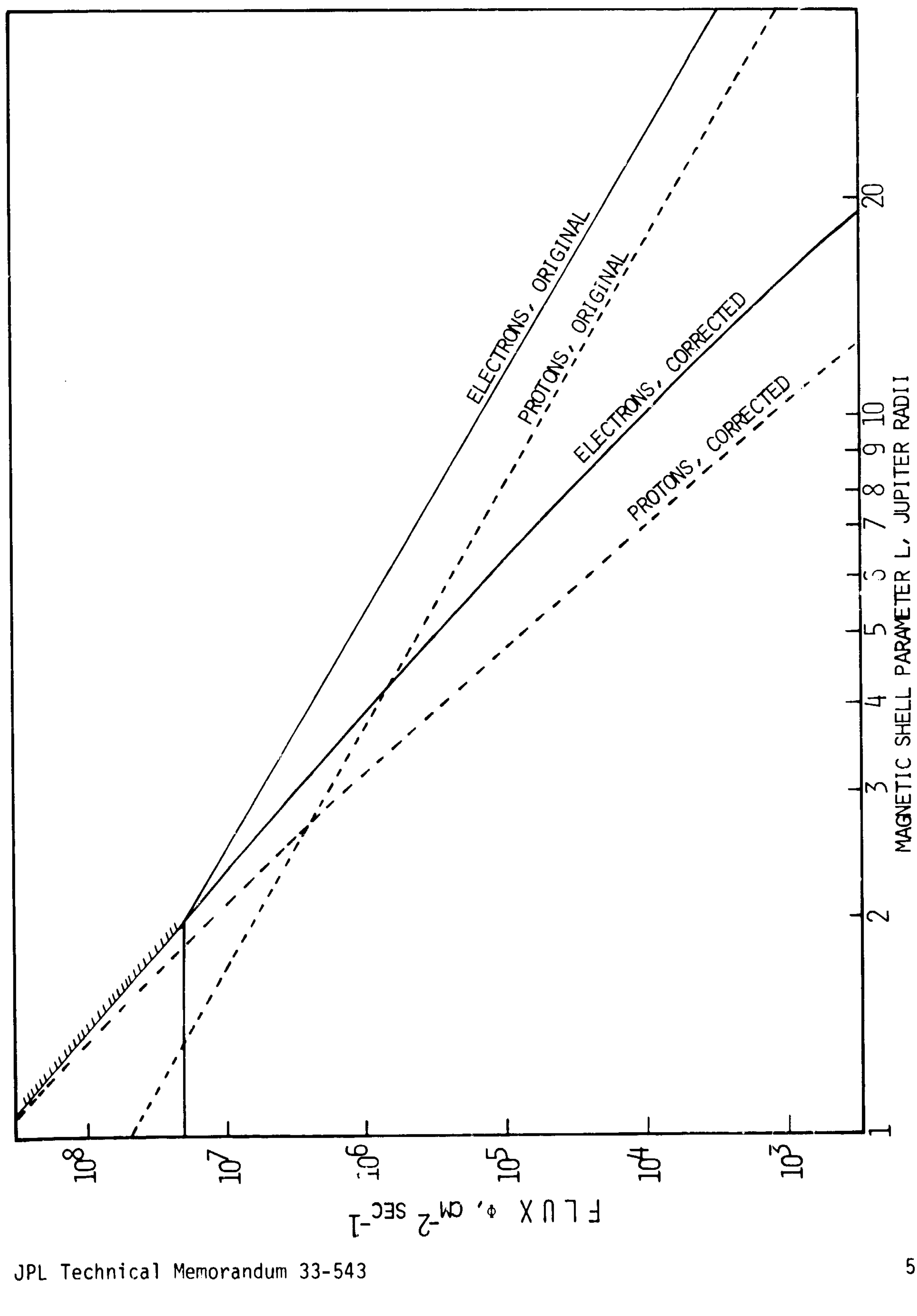

Figure 2. Nominal Workshop Models for Particle Flux vs L

If an analog of the Workshop model were devised for the Earth's magnetosphere, it would fit the observed properties rather poorly. We know that the Jovian magnetosphere differs from the magnetosphere of Earth in a number of essential features, but I doubt if any one can say with confidence that any specific difference makes the Workshop nominal model more (rather than less) likely to apply to Jupiter than to the Earth. One of the major arguments for the Workshop nominal model was that with a single set of parameters, this model did fit both the electron distribution (deduced from the decimetric radiation for L=2 to L=3) and the electron distribution expected in the solar wind. However, this was based on a nonrelativistic argument and the fit is not as good when done correctly. It is easily seen by extrapolation (from Figure 1) that in order to get protons down to 1 keV and electrons down to 100 eV, it is required that the magnetosphere extend to L=160.

The Workshop model ignores the problem of losses to the Galilean satellites. If diffusion for L=6 to L=20 is sufficiently rapid, this may be valid; but if diffusion continues to be rapid on to L=1.2, losses to Jupiter itself will be very large and may invalidate the model. If each satellite were surrounded by a substantial magnetosphere into which no Jovian field penetrated, there would be no losses; but this seems unlikely. If the satellites were so highly conducting that they were completely diamagnetic, the electron losses would be very substantially reduced and the electron fluxes at L=2 could easily be produced by diffusion; but the protons with their larger radii of gyration could well be lost in sufficient numbers at Io to substantially reduce the proton flux inside L=6. This situation is actually very complicated because the Jovian field would eventually penetrate the satellite for any reasonable conductivity and a very complicated topology of the field lines would be produced.

It is worth mentioning two other features of the Workshop nominal model that are not so much deficiencies of the underlying assumptions as of the calculation of the expected fluxes. One is the lack of attention to the effects of the distribution over energy and pitch angle of the particles;

the other is the omission from the analysis of the effects of losses at small L to Jupiter. Unless diffusion at small L is much slower than at large L, it can make the flux curves flatter over a considerable range of L.

The following is an alternative simple nominal model: Assume that outside L=10, the radiation levels are much like those in the Earth's radiation belts. Between L=6 and L=10, assume that the Galilean satellites reduce the flux of energetic particles to very low levels. Inside L=6, assume that there are no mechanisms that accelerate many protons to high energies, but that plasma instabilities associated with the decametric radiation (or with the interaction between Io and the Jovian magnetosphere) accelerate the electrons required to produce the synchrotron radiation. Assume that between L=1 and L=6, electrons are spread by L-shell diffusion, being lost to Io at L=6, to Jupiter mainly for $L<1.5$, and by synchrotron radiation. Then the electron flux would be rather like that in the corrected Workshop nominal model from L=1 to L=6 or L=10, and the proton flux in this region would be negligible.

The weakest points of this model are 1) the absence of a specific mechanism by which the electrons are accelerated and 2) the possibility that losses to Io might render ineffective any acceleration in the neighborhood. But it does not seem implausible that there should be such mechanisms. This is not put forward as the most plausible model but only as one sample of a variety of possible nominal models, none of which are drastically less probable than the others on the basis of current knowledge. In this situation, it seems unreasonable to fix on one such model as the basis for spacecraft design, even though from an engineering design point-of-view, it is easier to work with a single model that is actually almost surely incorrect but which has been carefully selected as having the fewest known objectionable features.

PRECEDING PAGE BLANK NOT FILMED APPENDIX B

POST-WORKSHOP MODELS OF JUPITER'S RADIATION BELTS*

Neil Divine**

INTRODUCTION

Models for the charged particle populations of Jupiter's trapped radiation belts were derived at the Jupiter Radiation Belt Workshop on the basis of several assumptions which represented a consensus of those scientists in attendance. It has been possible to improve these models on the basis of work performed after the Workshop concluded. These improvements affect the models in two major ways: 1) the effects of special relativity on the particle energy and flux dependences in the magnetosphere have been included in a derivation based on L-shell diffusion with conservation of the magnetic moment (ref. 1); and 2) quantitative, written conclusions have become available for the limit which ion-cyclotron instability places on the proton population (refs. 2 and 3). These developments have been circulated and discussed among several of the workshop participants***, who concluded that appropriate modifications should be made in the workshop models. Accordingly, a new set of models, which incorporates these developments in a way as consistent as possible with the original workshop assumptions and conclusions, is described in the following pages.

THEORETICAL BACKGROUND

The assumptions adopted at the Workshop include three which require detailed physical derivation and algebraic formulation before they can be

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** Jet Propulsion Laboratory, Pasadena, California 91103.

*** Particularly, Beck; Coroniti; Davis; Divine; Gulkis; Kennel; Thorne; and Warwick (who met at JPL on Tuesday, 9 November, 1971).

applied to the creation of models for Jupiter's charged particle population. These are: 1) the conservation of magnetic moment during L-shell diffusion (all models), 2) the equilibrium flux relationships in L-shell diffusion (all models), and 3) the energy, flux, and lifetime relationships through which ion-cyclotron instability limits the population (upper limit protons, only). The required derivations are performed elsewhere (refs. 1 through 3), and only the results and their interpretation are described below. The notation used is defined at the conclusion of the text.

Conservation of Magnetic Moment - According to Davis (ref. 1), the magnetic moment which is conserved in diffusion should be expressed as $\mu = p_{\perp}^2/2m_0B$, if it is to be described consistently with the requirements of special relativity. For particles in flat helices (for most of the particles under consideration, this is a good approximation), the relativistic relationship between E and $p_{\perp}$ is

$$E = m_0c^2\left[\left(\frac{p_{\perp}^2}{m_0c^2} + 1\right)^{\frac{1}{2}} - 1\right] \quad . \tag{1}$$

Thus, the conservation of magnetic moment in L-shell diffusion requires that if the particles have energy E_1 at a location where the field strength is B_1, then at a location where the field strength is B, the energy is

$$E = m_0c^2\left(\left\{\left[\left(\frac{E_1}{m_0c^2} + 1\right)^2 - 1\right]\frac{B}{B_1} + 1\right\}^{\frac{1}{2}} - 1\right) \quad . \tag{2}$$

If the energies E and E_1 are much less than m_0c^2, and if B is proportional to L^{-3}, equation 2 simplifies to the well-known relation for non-relativistic particles diffusing in a dipole field, namely

$$E = E_1\left(\frac{L_1}{L}\right)^3 \quad . \tag{3}$$

Equilibrium Flux in L-Shell Diffusion - Davis (ref. 1) has performed a brief derivation based on Liouville's Theorem which should apply to a population undergoing L-shell diffusion if the diffusion time (from the source to the point of interest) is shorter than the lifetime against loss (everywhere along the diffusion "path"). The result relates Φ and B locally to Φ_1 at the location where $B = B_1$, as follows:

$$\Phi = \Phi_1\left(\frac{B}{B_1}\right)^2\left(\frac{E_1}{m_0c^2} + 1\right)\Bigg/\left\{\left[\left(\frac{E_1}{m_0c^2} + 1\right)^2 - 1\right]\frac{B}{B_1} + 1\right\}^{\frac{1}{2}} . \qquad (4)$$

If the energies E and E_1 are much less than m_0c^2, and if B is proportional to L^{-3}, equation 4 simplifies to the following relation for non-relativistic particles diffusing in a dipole field

$$\Phi = \Phi_1\left(\frac{L_1}{L}\right)^6 . \qquad (5)$$

The derivations have been performed in a way that makes them applicable to any population for which the flux is distributed narrowly near an energy, in which case equations 2 through 5 can be interpreted as applying to E_0 as a local characteristic energy and Φ_0 as a local integral flux.

Ion-Cyclotron Instability - Kennel (ref. 2) and Thorne and Coroniti (ref. 3) have derived a representation of the results to be expected if an energetic proton population interacts with waves in the local plasma at frequencies near the ion cyclotron frequency, given by $\Omega^+ = eB/m_0c$ (here and below, Gaussian units are intended). Under certain conditions, an instability can develop in which energy flows from the energetic particles into resonant plasma waves, and the flux of energetic particles is thereby limited. The conditions are, first, that the energetic particles have energies greater than a critical energy $E_c \approx B^2/8\pi N$; and, second, that the characteristic time for the source of the energetic particles be larger than the loss time through the resonant interaction, $\tau_{min} \approx 8L^4R_J(2E/m_0)^{-\frac{1}{2}}$ in this case. If these conditions apply, the flux of particles with energy greater than E_c is limited by this instability to a value given by $J_{lim} \approx Bc/\pi eLR_J$.

The approximations in the foregoing expressions imply the omission of factors which are estimated to be of order unity for the particle populations considered.

NOMINAL ELECTRONS

Assumptions -

(1) Earth-based observations of UHF flux density and/or brightness temperatures at various wavelengths and the interpretation of these data in terms of synchrotron radiation are correct.

(2) UHF beaming and polarization data and their interpretation are correct.

(3) L-shell diffusion of electrons occurs from values at L=2 connecting with solar wind electrons which penetrate the magnetosheath.

(4) Conservation of the magnetic moment μ applies for the particles undergoing L-shell diffusion.

(5) A 10-gauss equatorial surface magnetic field strength is a reasonable nominal value for Jupiter.

(6) Jupiter's magnetic field is roughly that of a dipole, i.e., describable by magnetic shell parameter L and magnetic latitude ϕ, in the same way as the Earth, such that the local magnetic field strength is given by

$$B = (B_0 L^{-3})[1 + 3(\sin\phi)^2]^{\frac{1}{2}} (\cos\phi)^{-6} \quad ,$$

except for considerable distortion at the boundary with the solar wind.

(7) The derivation performed by Warwick (ref. 4) yields reasonable nominal values for the energy (E_0 = 6.2 MeV) and the flux ($\Phi_0 = 2 \times 10^7$ cm^{-2}sec^{-1}) of the radiating electrons in the region $1 < L \leq 2$, consistent with assumptions 1 and 2, above.

(8) The energy spectrum of the particles is narrowly distributed about some local characteristic energy whose variation is determined by assumption 4.

Model Specification -

$$\left.\begin{array}{l} E_0 = 6.2 \text{ MeV} \\ \\ \Phi_0 = 2.0 \times 10^7 \text{ cm}^{-2}\text{sec}^{-1} \end{array}\right\} \quad \text{for } 1 < L \leq 2$$

$$E_0 = (0.51)\left[\left(\frac{1377}{L^3} + 1\right)^{\frac{1}{2}} - 1\right] \text{ MeV}$$

$$\Phi_0 = \frac{1.7 \times 10^{10}}{L^6}\left(\frac{1377}{L^3} + 1\right)^{-\frac{1}{2}} \text{ cm}^{-2}\text{sec}^{-1}$$

for $2 \leq L < 50$

$$\Phi_E = \Phi_0\left(1 + \frac{E}{E_0}\right) exp\left(- \frac{E}{E_0} - \frac{\phi^2}{1000}\right)$$

for $1 < L < 50$

Remarks - Assumptions 1 through 8 suffice for the derivation of the model specification when the relativistic diffusion equations (2 and 4) are evaluated at L_1=2 (where B_1 = (10 gauss)/$(2)^3$ = 1.25 gauss, E_1 = 6.2 MeV,and $\Phi_1 = 2.0 \times 10^7 \text{ cm}^{-2}\text{sec}^{-1}$). In particular, the energy and latitude distributions are arbitrary ones consistent with assumptions 2 and 8.

If the magnetic moment conservation (on which the model energy dependences are based) is extended (using equation 2) to the interplanetary magnetic field strengths expected in the solar wind near Jupiter (namely, about $1\gamma = 10^{-5}$ gauss), the corresponding electron energy is 350 eV. This energy is much greater than both flow and thermal electron energies in the solar wind, but it is less than typical values of the proton flow energy in the solar wind (about 1 keV)*; the electrons could conceivably have acquired some of the proton energy in a thermalization process behind the shock front (at the solar wind boundary near Jupiter). The electron flux predicted by the model evaluated at L = 50 (near the magnetopause) is 1 $\text{cm}^{-2}\text{sec}^{-1}$, which is much less than the directed electron flux expected near Jupiter in the solar wind (about 10^7 $\text{cm}^{-2}\text{sec}^{-1}$). Thus, the solar wind is a plausible source of diffusing electrons in this model, and assumptions 3 and 4 are reasonable ones. The remaining assumptions are based more directly on available data and do not require additional justification here, except that assumption 8 should be examined for consistency with the latest UHF data for Jupiter (it has been suggested that new data near 80 megahertz contradict this assumption).

* This corresponds to a flow speed of 440 km/sec.

UPPER LIMIT ELECTRONS

Assumptions - Items 1 through 8 are assumed for this model as well, with the additional assumption that:

(9) The flux and energy inferred near L = 2 from the UHF data [cf assumptions (1) and (7)] are each uncertain by a factor of three because of the combined uncertainties in the magnetic field strength, UHF beaming and polarization inferences, the UHF bandwidth, and peaking of the electron distribution in L.

Model Specification -

$$E_0 = 20 \text{ MeV}, \quad \Phi_0 = 6.0 \times 10^7 \text{ cm}^{-2}\text{sec}^{-1} \qquad \text{for } 1 < L \leq 2$$

$$E_0 = (0.51)\left[\left(\frac{12930}{L^3} + 1\right)^{\frac{1}{2}} - 1\right] \text{MeV}, \quad \Phi_0 = \frac{1.5 \times 10^{11}}{L^6}\left(\frac{12930}{L^3} + 1\right)^{-\frac{1}{2}} \text{cm}^{-2}\text{sec}^{-1} \qquad \text{for } 2 \leq L < 50$$

$$\Phi_E = \Phi_0\left(1 + \frac{E}{E_0}\right) exp\left(-\frac{E}{E_0} - \frac{\phi^2}{1000}\right) \qquad \text{for } 1 < L < 50$$

Remarks - In this case, the extension of magnetic moment conservation into the solar wind (via eq. 2) yields an electron energy of 3.3 keV; no electrons, and very few protons have such high energies in the solar wind, but only by a factor of about two. The model electron flux at L = 50 is 10 $\text{cm}^{-2}\text{sec}^{-1}$, again much smaller than the directed electron flux (10^7 $\text{cm}^{-2}\text{sec}^{-1}$) expected in the solar wind near Jupiter. Thus, assumptions 3 and 4 are marginally reasonable for this model.

NOMINAL PROTONS

Assumptions - Items 4 through 8 are assumed for this model as well, with the additional assumptions that:

(10) L-shell diffusion of protons obtains from the magnetosheath all the way in to L = 1.

(11) Diffusion of protons past the satellites occurs without interference.

(12) The number density of energetic protons is the same as the number density of relativistic electrons at L = 2 in the workshop nominal electron model.

(13) The proton energy (and energy density) at L = 2 is ten times the electron energy (and energy density) to account for the greater solar wind proton energy at the magnetosheath.

(14) No losses occur on time scales shorter than the diffusion times for the protons or otherwise limit the proton fluxes.

Model Specification -

$$\left.\begin{aligned} E_o &= (938)\left[\left(\frac{1.06}{L^3} + 1\right)^{\frac{1}{2}} - 1\right] \text{ MeV} \\ \Phi_o &= \frac{4.7 \times 10^8}{L^6}\left(\frac{1.06}{L^3} + 1\right)^{-\frac{1}{2}} \text{ cm}^{-2}\text{sec}^{-1} \\ \Phi_E &= \Phi_o\left(1 + \frac{E}{E_o}\right) exp\left(-\frac{E}{E_o} - \frac{\phi^2}{1000}\right) \end{aligned}\right\} \quad \text{for } 1 < L < 50$$

Remarks - In this case, the extension of magnetic moment conservation into the solar wind (via eq. 2) yields a proton energy of 495 eV, which is comparable to the proton flow energy in the solar wind (about 1 keV). The model proton flux at L = 50 is 0.03 $cm^{-2}sec^{-1}$, much smaller than the directed proton flux about 10^7 $cm^{-2}sec^{-1}$) expected in the solar wind near Jupiter. Thus, assumptions 4, 10, 12, and 13 are reasonable for this model. Assumptions 11 and 14 have been challenged (particularly on the basis of work reported by Hess and Mead at the workshop), but the assumptions stated reflect the majority view among workshop participants.The proton flux limit derived for the upper limit proton model is not below the flux levels of this model, consistent with assumption 14.

UPPER LIMIT PROTONS

Assumptions - Items 4 through 8, 10, and 11 are assumed for this model as well, with the additional assumptions that:

(15) A solar wind trapping fraction of 10^{-3} ties down the diffusion flux at large L values.

(16) Ion-cyclotron instability considerations limit the flux at intermediate L values and tie down the diffusion flux at small L values.

(17) The flux of solar wind protons is specified reasonably by

$$(2.6 \times 10^8) r^{-2} \ \mathrm{cm^{-2} sec^{-1}} \quad ,$$

where r is the distance in AU from the Sun and the constant represents the quiet solar wind proton flux at the Earth's orbit.

(18) The plasma concentration in the equatorial plane of Jupiter's magnetosphere is specified reasonably by Figure 11 in reference 5.

(19) The diffusion rate has the same L-dependence as the fluctuating electric field mechanism, normalized to yeild the minimum diffusion rate necessary to get the protons past Io (cf. ref. 3).

(20) The proton energy at L=2 could be 100 MeV, somewhat greater than in the nominal model.

Model Specification -

$$\Phi_0 = \frac{10^{12}}{L^6}\left(\frac{1.8}{L^3} + 1\right)^{-\frac{1}{2}} \mathrm{cm^{-2} sec^{-1}} \qquad \text{for } 1 < L \leq 6$$

$$\Phi_0 = (2.8 \times 10^{10}) L^{-4} + (5.2 \times 10^7)\, exp\, [-(12-L)^2]\ \mathrm{cm^{-2} sec^{-1}} \qquad \text{for } 6 \leq L \leq 12$$

$$\Phi_0 = \frac{1.6 \times 10^{14}}{L^6}\ \mathrm{cm^{-2} sec^{-1}} \qquad \text{for } 12 \leq L < 50$$

$$\left.\begin{aligned} E_0 &= (938)\left[\left(\frac{1.8}{L^3} + 1\right)^{\frac{1}{2}} - 1\right] \mathrm{MeV} \\ \Phi &= \Phi_0\left(1 + \frac{E}{E_0}\right) exp\left(-\frac{E}{E_0} - \frac{\phi^2}{1000}\right) \end{aligned}\right\} \quad \text{for } 1 < L < 50$$

Remarks - In addition, an interpolation formula has been created to represent the flux for the region between the tie-down points in assumptions 15 and 16; in the inner portion of this region its L-dependence resembles that of the limiting flux for ion cyclotron stability.

In this case, the extension of magnetic moment conservation into the solar wind (via eq. 2) yields a proton energy of 840 eV, which is comparable to typical values of the proton flow energy in the solar wind (about 1 keV). The flux at L=50 is governed by assumptions 15 and 17. Thus, the solar wind is a reasonable source for protons in this model.

The model is not particularly sensitive to changes in the plasma density N, taken here as in assumption 18. For the peaked plasma distribution given in reference 5, the critical energy $E_c \approx B^2/8\pi N$ falls very rapidly as L increases, whereas even for a uniform plasma density, the critical energy E_c is proportional to L^{-6} (because of its proportionality to B^2). The limiting flux predicted by ion-cyclotron instability controls the actual flux only if the characteristic energy E_0 (approximately proportional to L^{-3}) exceeds E_c. Thus, the limit applies only in a region of L greater than some cutoff L_c. If assumption 18 holds, the solution $L_c = 6.0$ is obtained (ref. 3, Figure 1) for a magnetic moment $\mu \approx 100$ MeV/gauss (this is close to the case for this model, in which $\mu = 84$ MeV/gauss). Even if the plasma density N is uniform at 1, 10, or 100 cm^{-3}, the corresponding solutions for L are 14, 6, and 3 R_J for $\mu = 100$ MeV/gauss; and L_c is proportional to $(B_0/\mu)^{1/3}$ (i.e., not sensitive to changes in μ or surface field B_0). This considerable range for L_c does not, however, change the model significantly for $L<L_c$, because the slopes of the limiting and diffusion fluxes are similar (L^{-4} contrasted with L^{-6}; the limiting flux itself is $(2.8 \times 10^{10}\ cm^{-2}sec^{-1})L^{-4}$, independent of N). If $L_c \neq 6$, the flux for $L<L_c$ should be multiplied by $(L_c/6)^2$, and for $3<L_c<14$, this factor ranges between 0.25 and 5.5, representing excursions of less than one order of magnitude from the model chosen, which represents the best estimate of an appropriate upper limit.

The inner boundary of the outer diffusion region occurs where the loss time $\tau_{min} \approx (1.4\ sec)L^{11/2}$ equals the diffusion time; outside this boundary, the loss time is long compared to the source time and the limiting flux does not apply. According to assumption 19 and reference 3, the diffusion time for protons to go one Jupiter radius is $(6 \times 10^{12}$ sec$)/L^6$; the boundary thus occurs near L=12. The flux will exhibit a local maximum at this boundary and its value there will be sensitive to the boundary location (proportional to L^{-6}). In particular, if the diffusion is much faster than the mechanism suggested in assumption 19, this boundary moves inward and the local flux goes up. However, this does not affect the model in the inner portion of the belts, and for L>10, the model energies are less than 1 MeV; thus, the choice of this boundary has no major consequences. In this model, the boundary is taken at L=12, on the basis of assumption 19 and reference 3.

For $L \leq 3$ the proton energy flux in this model is comparable to or greater than that of sunlight (about 5×10^4 erg/cm^{2}sec); thus if the model is realistic its effect on surface phenomena of JV (Amalthea, at 2.54 R_J) might be significant (private communication, L. Davis, Jr.).

SUMMARY DESCRIPTION OF MODELS

Table I presents formulas and parameters for nominal and upper limit models of relativistic electrons and energetic protons in Jupiter's radiation belts. The models are consistent with the assumptions adopted at the Jupiter Radiation Belt Workshop, with a relativistic derivation of the magnetic moment conservation and L-shell diffusion flux (ref. 1), and with a quantitative consideration of the likely effects of ion cyclotron instability on an upper limit proton model (refs. 2 and 3). Figure 1 shows the flux parameter Φ_0 as a function of L in the magnetic equatorial plane, with an indication of the local characteristic energy. Table II evaluates the model fluxes in several energy intervals at the location of the peak electron fluxes in the belts (L=2 and ϕ=0). Because the precise location of the electrons responsible for the UHF emission is uncertain and because local particle loss mechanisms could be strong (e.g., satellite sweeping, particularly for the protons), an appropriate lower limit to the flux, at any given time and location, is zero.

To calculate particle fluxes from the formulas in Table I fo. a specific position (specified by distance R and latitude ϕ with respect to Jupiter) and energy interval (between E and E+ΔE), the following procedure should be employed.

1. Calculate the magnetic shell parameter L from $L = R/R_J(\cos\phi)^2$.

2. Evaluate the flux parameter Φ_0 (shown in Figure 1) and the characteristic energy E_0 from the first several rows in the table, chosen according to the value of L, the particle type, and the model required.

3. With the last formula in Table 1, calculate Φ_E, the particle flux for energy greater than E, for both end-points of the energy interval and take the difference to obtain $(\Delta\Phi)_E$, the flux in the interval of interest.

Table I. Formulas for Energetic Charged Particles in Jupiter's Trapped Radiation Belt

Model	Location	Flux Parameter, ϕ_0 ($cm^{-2}sec^{-1}$)	Characteristic Energy, E_0 (MeV)
Nominal	$1 < L \leq 2$	2.0×10^7	6.2
	$2 \leq L < 50$	$\frac{1.7 \times 10^{10}}{L^6}\left(\frac{1377}{L^3} + 1\right)^{-1/2}$	$(0.51)\left[\left(\frac{1377}{L^3} + 1\right)^{1/2} - 1\right]$
Upper Limit Electrons	$1 < L \leq 2$	6.0×10^7	20.0
	$2 \leq L < 50$	$\frac{1.5 \times 10^{11}}{L^6}\left(\frac{12930}{L^3} + 1\right)^{-1/2}$	$(0.51)\left[\left(\frac{12930}{L^3} + 1\right)^{1/2} - 1\right]$
Nominal Protons	$1 < L < 50$	$\frac{4.7 \times 10^8}{L^6}\left(\frac{1.06}{L^3} + 1\right)^{-1/2}$	$(938)\left[\left(\frac{1.06}{L^3} + 1\right)^{1/2} - 1\right]$
Upper Limit Protons	$1 < L \leq 6$	$\frac{1.0 \times 10^{12}}{L^6}\left(\frac{1.8}{L^3} + 1\right)^{-1/2}$	
	$6 \leq L \leq 12$	$(2.8 \times 10^{10})L^{-4} + (5.2 \times 10^7)\ exp\left[-(12-L)^2\right]$	$(938)\left[\left(\frac{1.8}{L^3} + 1\right)^{1/2} - 1\right]$
	$12 \leq L < 50$	$\frac{1.6 \times 10^{14}}{L^6}$	
Distributions with Energy and Latitude*	$\phi_E = \phi_0\left(1 + \frac{E}{E_0}\right) exp\left(-\frac{E}{E_0} - \frac{\phi^2}{1000}\right)$		

*Latitude ϕ in degrees only

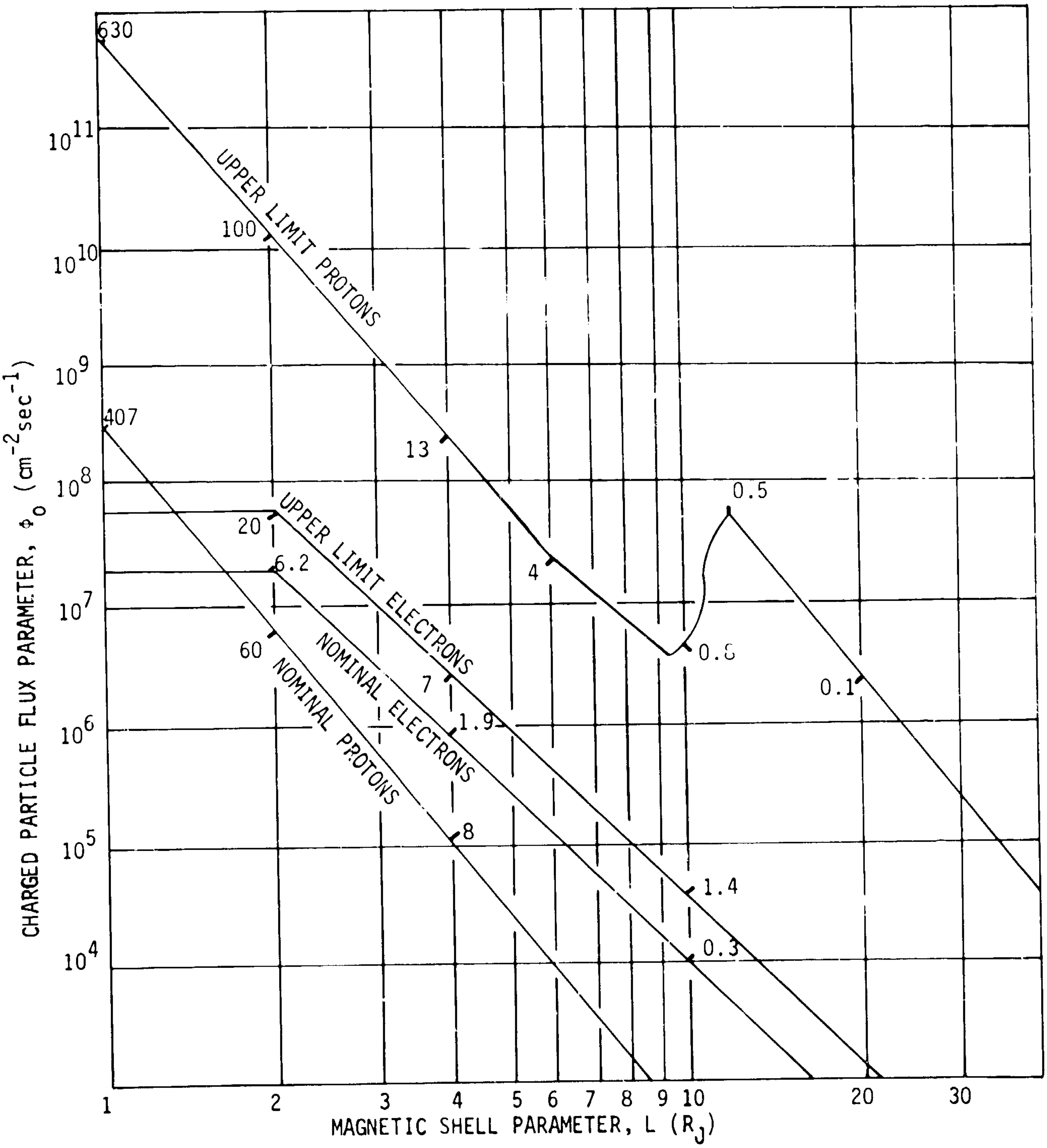

Figure 1. Fluxes of charged particles in Jupiter's trapped radiation belts, as functions of distance from the magnetic dipole in the magnetic equatorial plane. Local values of the characteristic energy E_0 are shown in MeV.

Table II. Energetic Charged Particle Fluxes for Individual Energy Intervals at the Location of the Peak Electron Fluxes in Jupiter's Trapped Radiation Belts ($L = 2$ and $\phi = 0$)

Particle Type	Energy Interval (MeV)	Flux, $(\Delta\phi)_E$ in $cm^{-2}sec^{-1}$	
		Nominal	Upper Limit
Electrons	1-3	1.5×10^6	5.4×10^5
	3-10	7.9×10^6	4.8×10^6
	10-30	9.5×10^6	2.1×10^7
	30-100	9.3×10^5	3.1×10^7
	100-300	34	2.4×10^6
	300-1000	0.0	300
Protons	1-3	7.4×10^3	5.5×10^6
	3-10	7.8×10^4	6.0×10^7
	10-30	5.4×10^5	4.6×10^8
	30-100	2.8×10^6	3.2×10^9
	100-300	3.2×10^6	7.6×10^9
	300-1000	2.8×10^5	2.8×10^9
	1000-3000	7.0	7.0×10^6
	3000-10000	0.0	0.041

NOTATION

B	local magnetic field strength, in gauss
B_0	B evaluated at Jupiter's equator, $B_0 \approx 10$ gauss
B_1	B evaluated at $L = L_1$
c	speed of light, $c = 3 \times 10^{10}$ cm/sec
E	charged particle kinetic energy
E_c	critical energy, above which ion cyclotron instability limits proton fluxes
E_0	local characteristic energy, in MeV
E_1	E or E_0 evaluated at $L = L_1$
e	proton charge, $e = 4.803 \times 10^{-10}$ esu
$J_{\ell im}$	limiting flux of protons with $E > E_c$ for ion cyclotron stability
L	magnetic shell parameter, in Jupiter radii
L_c	critical value of L; ion cyclotron instability limits proton fluxes for $L > L_c$
L_1	value of L at which E, B and Φ are known or specified
m_0	particle rest mass
N	plasma electron or proton concentration, in cm^{-3}
$p_\perp$	momentum component perpendicular to direction of magnetic field
R	distance from center of Jupiter
R_J	Jupiter's equatorial radius, $R_J = 71422 \pm 200$ km
r	distance from the Sun, in AU
$(\Delta\Phi)_E$	flux in an interval between E and $(E + \Delta E)$, in $cm^{-2}sec^{-1}$
μ	particle magnetic moment, in MeV/gauss
τ_{min}	characteristic time for particle loss in any pitch-angle scattering process (e.g., ion cyclotron instability)
Φ	flux of charged particles, $cm^{-2}sec^{-1}$
Φ_E	Φ evaluated for energies >E
Φ_0	local flux parameter
Φ_1	Φ or Φ_0 evaluated at $L = L_1$
ϕ	Jupiter magnetic latitude, in degrees
Ω^+	proton cyclotron frequency

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NASA — JPL — Coml., L.A., Calif.