N78-10132

Contents

1. The Plasma Environment at Geosynchronous Orbit

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1. INTRODUCTION

The scope of this paper is two-fold:

(1) To present a picture of the magnetosphere about geosynchronous orbit (GSO) to the nonspecialist, and

(2) To introduce a preliminary model which should be of use to spacecraft designers as well as certain others.

The emphasis of both the environmental discussion and the model presentation is to give information to investigators who are not necessarily engaged in magnetospheric research.

In designing this type of presentation, one must first ask, "why is it important?", and "who is the audience?". For purposes of this presentation, we assume that the importance of the plasma environment is due to the fact that it interacts with spacecraft surfaces to produce electrostatic charging. We will give only nodding recognition to the important and exciting geophysical implications of the plasma dynamics at GSO. Similarly, we will assume that a large fraction of the intended audience will not be intimately familiar with the specialized jargon of the magnetospheric physicist.

Finally, we acknowledge that this paper presents work in progress and that the many gaps in our understanding of the conditions of GSO will not be closed until after the GEOS and SCATHA missions are successfully completed.

The magnetosphere is a very complicated place, and GSO is located at the boundary of several distinct plasma regions. As can be seen from Figure 1 – which is a new version of a much used figure by W. Heikkila – the low altitude plasma is a low-temperature relatively high-density region, called the plasmasphere (a temperature of a few electron volts and densities of 10-1000 particles/cm^3, see Chappell[1]). Higher altitude plasma in general is much hotter and less dense (1000's of electron volts and 1 particle/cm^{-3}, see DeForest and McIlwain[2]). This is generally called the plasmasheet. Much of the physics governing spacecraft charging at GSO is determined by the interplay of these two regions as they move in and out past a space vehicle.

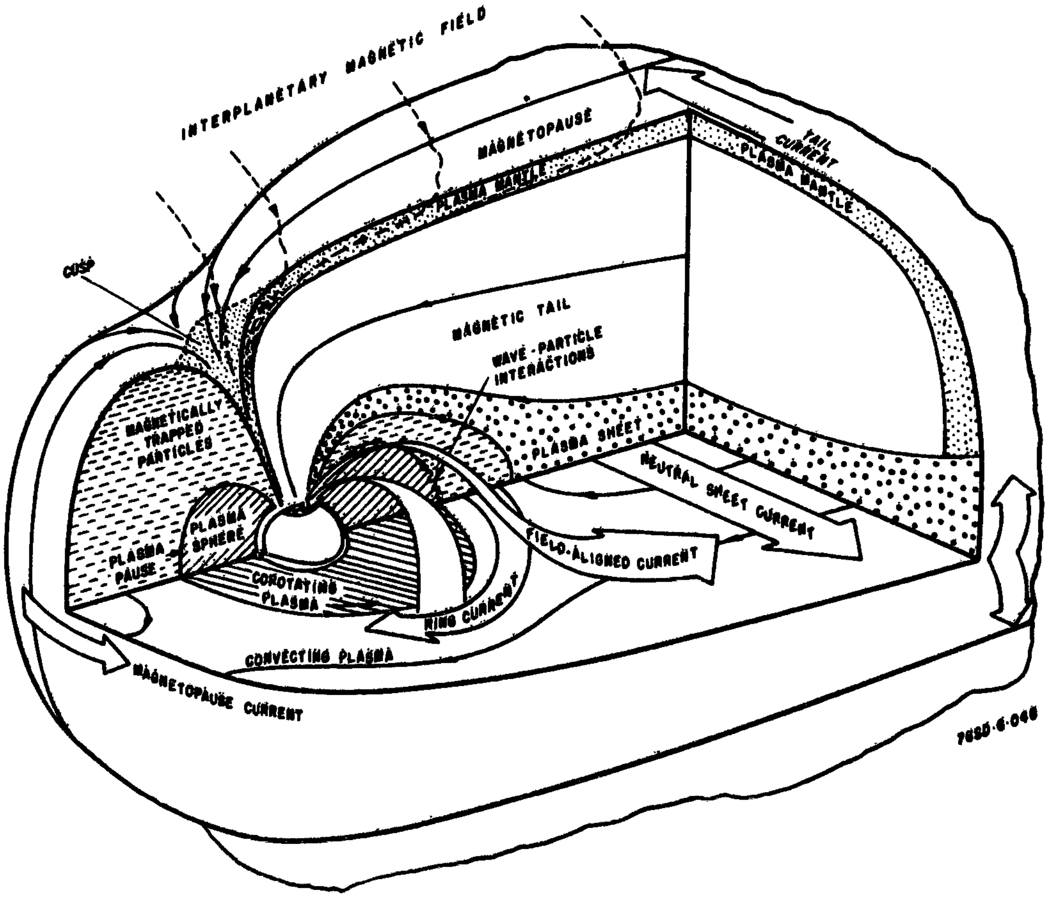

Figure 1. Magnetosphere (after Heikkila)

During geomagnetically active times, all the boundaries shown in Figure 1 tend to move inwards. This means that the magnetopause can occasionally pass inside at GSO and expose a vehicle there to the magnetosheath particles.[3,4] Russell (private conversation) has estimated that approximately 3 percent of the time a vehicle at GSO will be in the magnetosheath. At least one, ATS-5 was actually exposed to the unshocked solar wind.[5] No operating anomalies are known to be associated with these transitions. And since the characteristic energies of the magnetosheath particles are much lower than those of the plasmasheet, no further discussion of these regions will be presented here. However, a complete model must take these regions into account.

2. GENERAL MORPHOLOGY AND DYNAMICS

2.1 Global Variations

Although the theory of plasma dynamics in the magnetosphere is still being developed, rather simple considerations can be used to predict that the plasmasphere should not be spherically symmetrical at all, but should bulge on the dusk side. This has been shown repeatedly by both ground-based and in situ measurements.[1,6,7] Furthermore the boundary, called the plasmapause, moves inward with increasing activity. As a general rule, features of the plasmasphere co-rotate or nearly co-rotate with the earth until they dissipate and can no longer be observed. Also as a general rule, the density decreases strongly with increasing equitorial altitude. These rules are very approximate since we are really discussing a type of weather.

Since the plasmaspheric particles are not very energetic, their motions will be predominantly determined by local electric fields. This is contrasted with the more energetic plasmasheet particles which tend to be dominated by magnetic effects.

This difference in the dynamics of the two populations also determines certain differences in the nature of their spectra. Plasmasheet particles appear suddenly in injection events[2] which have a one-to-one correlation with ground based substorms.[8,9] After injection, electrons gradient drift to the East and the ions gradient drift to the West. The speed of the drift is proportional to the energy of the particle. At lower energies, these motions get modified by electric field effects. The net result is that even though the plasma is Maxwellian at the injection, the nature of the particles that will strike a vehicle surface depends strongly on where that vehicle is with respect to the location of the injection. In general, a vehicle will encounter high fluxes of electrons between midnight and dawn. This is simply because they move that way shortly after injection. Contrariwise, excess energetic ions can be encountered in the premidnight sector. This latter situation has not proven to be as hazardous to spacecraft operation as the former. Therefore, we will tend to emphasize the electron dynamics in what follows.

The electric fields present at GSO have not been measured directly, but they are of the order of mV/m. From this and the condition stated above, one can conclude that gross charge neutrality always holds for the plasma. That is, after an injection, a polarization field is set up as the particles try to gradient drift apart. This field then affects the sea of low-energy particles in such a way as to reduce it.

The magnetic field has been measured at GSO by a variety of space vehicles and is therefore reasonably well-known.

Using plasma data from ATS, McIlwain[10] derived a best fit static electric field for the magnetosphere after an injection* as shown in Figure 2. Note the closed field lines which bulge on the dark side. This delimits the approximate plasmapause.

With both electric and magnetic fields in hand, Mauk and McIlwain[11] could go one step further and show that injections occur with a sharp well-defined spiral boundary. This is shown in Figure 3. This boundary moves in and out with geomagnetic activity in a quantitative way. Confirmation of the existence of this boundary has been provided by Konradi et al[12] in their studies of EX 45 data.

This boundary can be used to predict approximately where a space vehicle will first encounter hot electrons and thus might become a useful tool for operational spacecraft. However, the calculations needed to make predictions cannot now be made on-line. Perhaps this will be a fruitful area for future research.

2.2 Time Variations

Substorms (or plasma injections) tend to occur approximately every three hours. Only rarely will a period as long as a day go by without any significant activity.[13] The giant storms which attract popular attention by creating bright aurorae at latitudes which are heavily populated and by affecting radio transmissions are composed by several substorms occurring in so rapid a succession that the magnetosphere does not have time to recover between them. Then each successive injection delivers particles deeper in. Both periods of extreme quiet and extreme activity can be predicted with some accuracy by solar observations. The same is not true of substorms. Whipple (this conference) has stated that he believes that a suitable precurser can be found for substorms, and Rostaker[14] has

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*Actual fields during injection are undefined and during very quiet times the field at GSO is much smaller than shown here. Therefore, this field is at best a useful approximation.

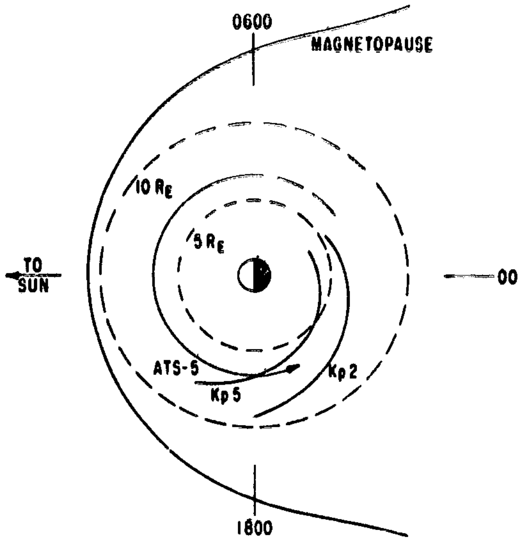

Figure 2. Electric Fields by McIlwain

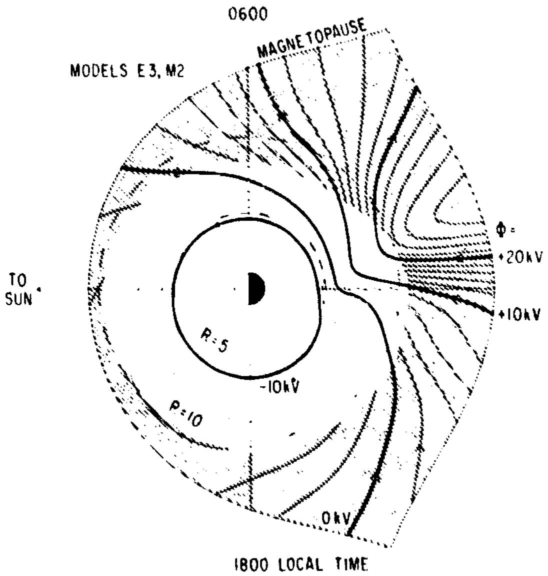

Figure 3. Injection Boundary (Mauk and McIlwain)

postulated a certain type of wave activity before a substorm based on observations from standard ground-based magnetometers.

On the longer time scale, the frequency of all kinds of geomagnetic activity is determined by the solar cycle and we are approaching a solar maximum so we can expect more activity in the next couple of years.

Recent work[15] has shown that there might be periods when the sun is very quiet and no sun spots or auroral activity is seen for tens of years. This is current research, but we are unlikely to enter such a quiet condition in time to affect design of present day spacecraft.

Time variations with periods much shorter than associated with substorms are probably not global in nature, but localized events as discussed in the next section.

3. DETAILED OBSERVATIONS AND EVENTS

3.1 Observations

The direct measurements of the plasma distribution function at GSO are very limited. In spite of the great popularity of this orbit for operational spacecraft, only three semiresearch oriented space vehicles have flown there (ATS-1, 5 and 6). Many spacecraft have made cuts through this region, but since these cuts come at large intervals (for example, 2 days) and last for only minutes, they do not allow detailed studies. Low altitude-high inclination vehicles can detect particles that will traverse the GSO equitorial region, but uncertainties about the proper mapping make inferences difficult (and a fruitful area for further research).

Although a low-energy instrument was carried on ATS-1,[16] it did not have the energy resolution necessary to measure the spectra. This means that most of our information comes from the UCSD instruments on ATS-5 and 6. We eagerly await the observations of GEOS (launch in Spring 1977) and SCATHA (launch in Fall 1978) to augment the data base. Of particular interest will be the mass spectrometer results and the various field measurements.

3.2 Waves

Many classes of waves exist in the magnetosphere with periods of many seconds to VLF waves. Some theorists would even consider substorms a wave phenomena.

It is far beyond the scope of this paper to review the types of waves that have been observed. Therefore, we will present a single example of a type of wave which might be able to affect spacecraft operations. This is a Pc4 wave of the type which has been seen on geosynchronous spacecraft equipped with magnetometers for quite some years.[17] However the work shown here – which is taken from a paper being prepared by DeForest, Cummings, and McPherson for submission to the Journal of Geophysical Research – is the first observation when both particle and field measurements were available. The spectrogram in Figure 4 shows the modulation produced in a detector parked looking West during the wave event (readers unfamiliar with spectrograms should refer to the description in DeForest and McIlwain[2]). Fortunately, this detector was parked while another detector faced East and a third looked radially outward. This allowed us to calculate the flow velocity implicit in the modulations. From that information and the known magnetic field, the complete wave can be described. (Strictly speaking, only the component of flow in the plane of the detectors is measured.)

The part of this type of wave which really concerns the spacecraft designer is that the modulations in Figure 4 represent flows of 150-200 km/sec with a period of 150 sec. By comparison, a 50 eV proton has only a speed of 100 km/sec. This means that first one side of the space vehicle than the other will experience a depletion of the lowest energy particles. We do not know yet what effects this might have.

We expect with the launch of SCATHA to detect waves interactions all the way up to VLF frequencies. Such waves might be able to couple directly into spacecraft harness and change logic states.

3.3 Field Aligned Fluxes

One of the outstanding discoveries of ATS-6 is the occasional presence of intense field-aligned fluxes of electrons.[18] Detailed studies of the general anisotropy are still in progress, but the situation at present is that a well-developed loss cone can exist for high-energy particles at the same time that a "source cone" or field-aligned flux exists for lower energy particles. Similarly, the electrons can show excess field-aligned fluxes at the same time that the ions show a loss cone. Examples of these situations are shown in Figures 5 to 8. These were taken from a talk given by Mauk.[19]

We do not yet know how these anisotropies fit into magnetospheric dynamics. Even worse, we are unable to quote good statistics on their occurrence since whether they are observed or not is in great part an artifact of the orbit and orientation of the detector.

However, we do know[20] that the fluxes of field-aligned electrons can at times completely dominate the charging in cavities at the ends of spacecraft. This is true even though the total anisotropic component is small compared to the isotropic component.

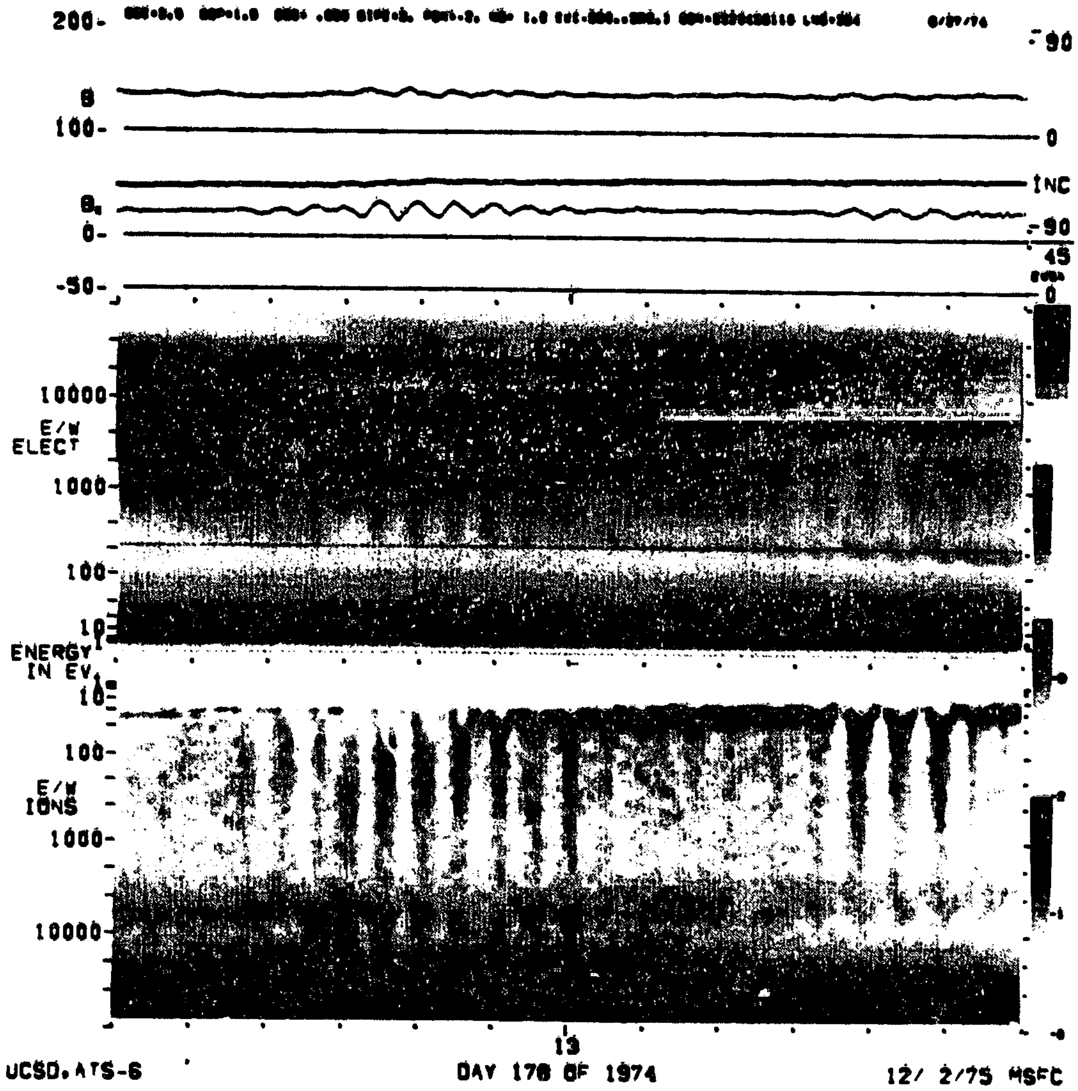

Figure 4. Spectrogram of Pc4 Event

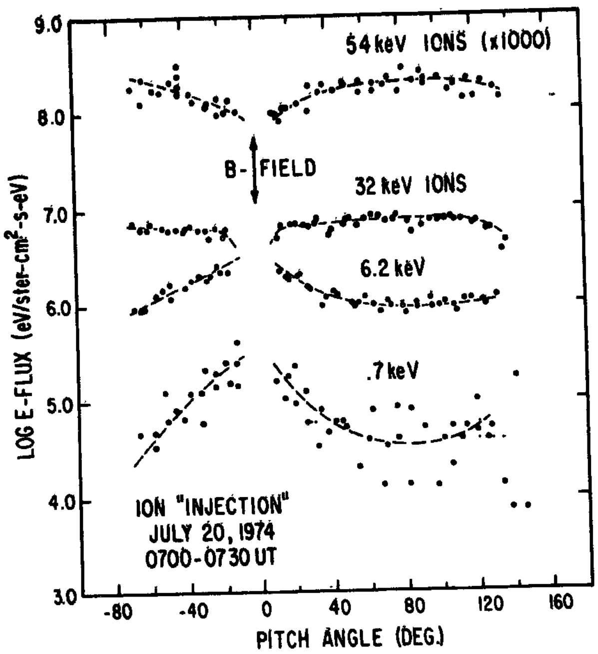

Figure 5. Particle Anisotropies From ATS-6

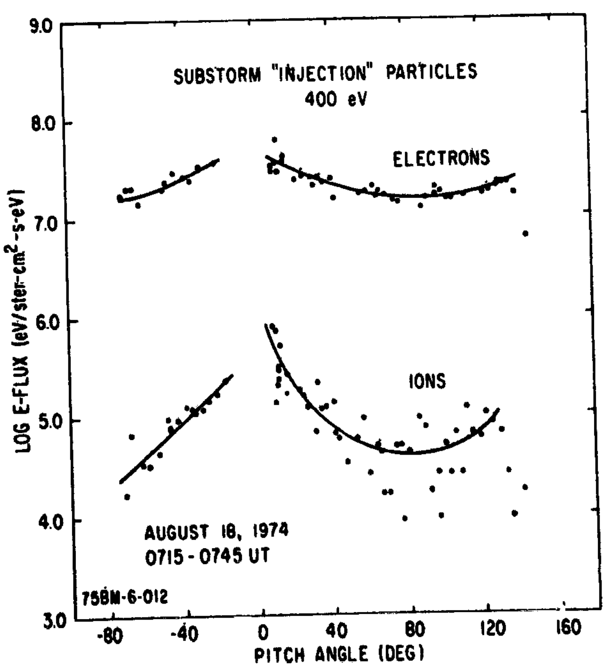

Figure 6. Particle Anisotropies from ATS-6

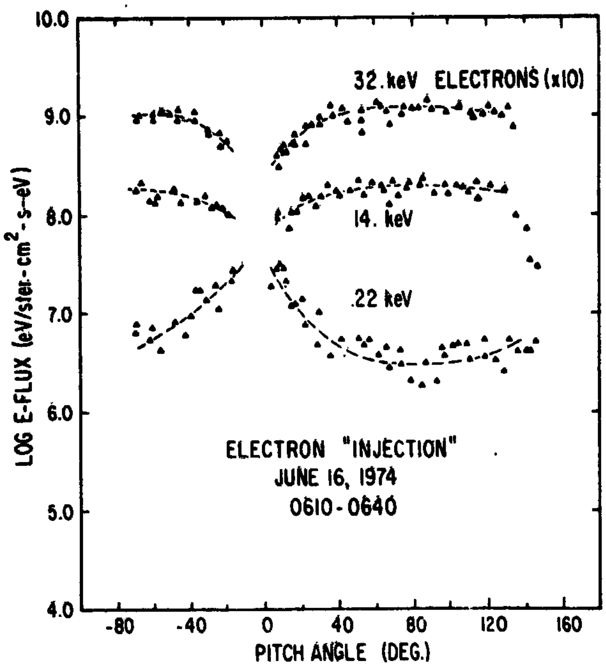

Figure 7. Particle Anisotropies from ATS-6

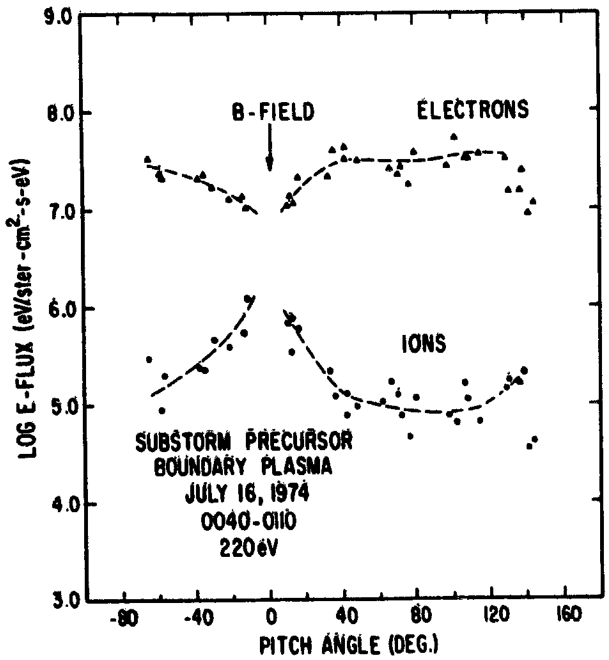

Figure 8. Particle Anisotropies from ATS-6

3.5 Comments

We are still finding new pl ma phenomena at GSO. We understand the ove.·· all patterns fairly well and are making progress on understanding such things as waves. But one must always remember that this is a very complex environment.

When certain classes of operating anomalies fail to correlate with substorm injections or other indications of activity, the reason might simply be that the spacecraft was inadvertently oriented in a manner that protected it. Next time around the spacecraft might slew in orbit or the magnetic field might tip. The new type of anomaly might be recorded. Since operational spacecraft do not normally carry either environmental monitors or even local noise counters, the r~~l cause of the event can only be guessed, and that guessing can be very expensiv.

A convenient comparison is to say that substorms are like the earthly thunderstorms that we can predict and understand reasonably well. Many of these unusual events are like tornados. We understand a little about them. We know they are associated with larger events, and they are potentially dangerous.

4. MODEL

The general problem of modeling this environment is quite difficult because of the inherent complexity of plasma interactions. One can easily name 21 different independent parameters that would have to be specified as a function of time to represent the environment. And that would be possible only by assuming a Maxwellian distribution for the various constituents.

The particular problem of providing a simple model to the spacecraft designer is also difficult since blindly specifying the worst case for all parameters could result in severe overdesign and waste.

The initial model proposed in this study was to select representative days from the five years of available ATS-5 data and add to this a model of field-aligned fluxes and low-energy plasmas that had been derived from the more recent ATS-6 data. This approach has the benefit of providing users with real data suitable for computer modeling in a relatively quick and low cost way.

Six days have been picked which have examples of many different types of activity.

However, the potential users at this conference have expressed a desire for an even simpler environmental specification even though they realize it would not be as definitive. Therefore, we are currently reassembling the available data to assemble such a simplified model in a timely fashion.

One observation that can be of use is shown in Figure 9. Data for a whole year were scanned to find those substorms which occurred in the immediate

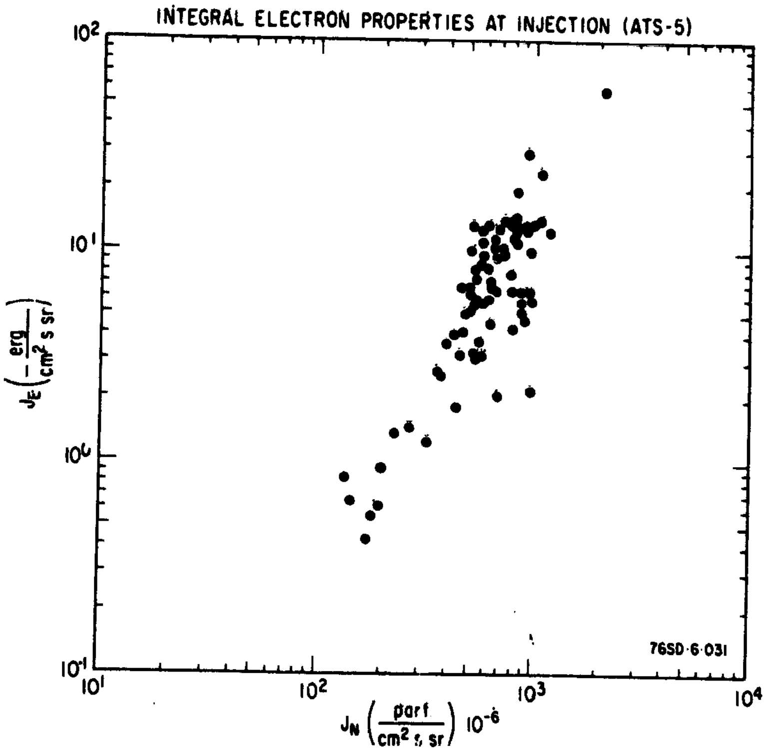

Figure 9. Energy Flux Versus Number Flux of Electrons at GSO.

vicinity of ATS-5. Then the measured energy flux was plotted against the number flux. Far from being random, the points are well-ordered, if somewhat confusing. A slope of 1 on the figure would indicate a constant temperature. That is definitely not the case, but no suitable explanation for the shape has yet been proposed. Still we can fit a curve to these points and eliminate at least one variable in the model.

We will use such simplifications and assumptions to derive a probability of encountering fluxes above a given level. Then the designer can determine an appropriate design specification based on his particular mission. The exact form of this simplified specification has not been determined at the time of this writing, but we hope to complete it before the end of the year. Work will continue of the more complete model, but only after the simplified version has been distributed.

Acknowledgment

This work was supported by Air Force Contract F19628-76-C-0214.

References

1. Chappell, C.R. (1970) A study of the influence of magnetic activity on the location of the plasmapause as measured by OGO 5, J. Geophys. Res. 75:50.

2. DeForest, S.E., and McIlwain, C.E. (1971) Plasma clouds in the magnetosphere, J. Geophys. Res. 76:3587.

3. Skillman, T.L., and Sugiura, M. (1971) Magnetopause crossing of the geostationary satellite ATS-5 at 6.6 R_E, J. Geophys. Res. 76:44.

4. Bogott, F.H., and Mozer, F.S. (1971) Magnetopause electric field inferred from energetic partial measurements on ATS-5, J. Geophys. Res. 76:892.

5. DeForest, S.E. (1973) Detection of solar wind at synchronous orbit, J. Geophys. Res. 78:1195.

6. Carpenter, D.L. (1970) Whistler evidence of the dynamic behavior of the duskside bulge in the plasmasphere, J. Geophys. Res. 75:3825.

7. Reasoner, D.L., Lennartson, W., and Chappell, C.R. (1976) The relationship between ATS-6 spacecraft charging occurrence and warm plasma encounters, Spacecraft Charging by Magnetospheric Plasmas, Edited by A. Rosen, MIT Press.

8. Akasofu, S.I., DeForest, S.E., and McIlwain, C.E. (1974) Auroral displays near the foot of the field line of the ATS-5 satellite, Planet. Space Sci. 22:25.

9. Eather, R.A., Mende, S.B., and Judge, R.J.R. (1976) Plasma injection at synchronous orbit and spatial and temporal auroral morphology, J. Geophys. Res. 81:2805.

10. McIlwain, C.E. (1971) Plasma convection in the vicinity of the geosynchronous orbit, Earth Magnetospheric Processes, Edited by B. M. McCormac, R. Reidel, Dordrecht-Holland.

11. Mauk, B., and McIlwain, C. (1974) Correlation of K_p with the substorm-injected plasma boundary, J. Geophys. Res. 79:3193.

12. Konradi, A., Semer, C., and Fritz, T. (1975) Substorm-injected protons and electrons and the injection boundary model, J. Geophys. Res. 80:543.

13. Akasofu, S.I. (1968) Polar and Magnetospheric Substorms, Springer, New York.

14. Rostoker, G. (1968) Macrostructure of geomagnetic bays, J. Geophys. Res. 73:4217.

15. Eddy, J.A. (1976) The maunder minimum, Science 192:1189.

16. Freeman, J.W.J., Maguire, J.J. (1968) On the variety of partial phenomena discernible at the geostationary orbit via the ATS-1 satellite, Am. Geophys. 24 (No. 1).

17. Cummings, W.D., Mason, F., and Coleman Jr., P.J. (1972) Some Characteristics of the low-frequency oscillations observed at ATS-1, J. Geophys. Res. 77:748.

18. McIlwain, C.E. (1976) Auroral electron beams near the magnetic equator, Physics of the Hot Plasma in the Magnetosphere, Edited by B. Hulquist and L. Stenflo, Plenum Publishing Co., New York.

19. Mauk, B. (1975) Magnetospheric substorm pitch angle distribution, EOS 56:423.

20. Vogl, J.L., Sanders, M.L., and DeForest, S.E. (1976) Substorm-induced spacecraft-charging current from field-aligned and omnidirectional particles, Spacecraft Charging by Magnetospheric Plasmas, Edited by A. Rosen, MIT Press.

Appendix A

Preliminary Environmental Specification for Geosynchronous Orbit

1. OMNIDIRECTIONAL ELECTRON FLUXES

Data for a complete year (1970) were scanned using ATS-5. The relative occurrence of number fluxes greater than any amount was computed and is shown in Figure A1. The data included in the figure are not all injections, but only those that occurred in the immediate vicinity of the spacecraft and hence did not have time to disperse by gradient drifting before the measurement was made. The last measured point is at 1.5×10^{-4} part/cm^2 sr sec. The curve has been arbitrarily extended to 100 percent at 10^{-6}. From this curve, we can define two relevant fluxes:

(1) 10^{-3} part/cm^2 sr sec for typical exposure.

(2) 10^{-2} part/cm^2 sr sec for extreme exposure.

The second limit is somewhat arbitrary, but should be a safe design limit. The probability of exceeding 10^{-2} in a year is probably less than 1 part in 10^4.

Using the electron correlation data of the main text, we can now estimate the corresponding energy fluxes as:

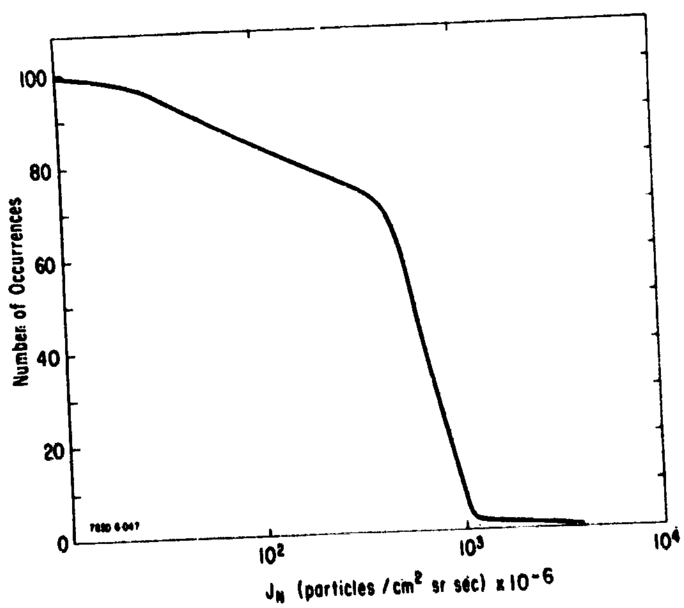

Figure A-1. Relative Occurrence of Number Fluxes Greater than any Amount.

(1) 16 erg/cm^2 sec eV (average energy = 16,000 ev).

(2) 770 erg/cm^2 sec eV (average energy = 77,000 ev).

The worse case from the spacecraft charging view probably comes when this electron flux is neutralized not by the corresponding injected ion flux, but by lower energy ions. If we assume that the sunlit side of the vehicle is held at ground while the dark side is bombarded by these fluxes, then the maximum electrostatic stress is placed on the surface.

2. UNIDIRECTIONAL ELECTRON FLUXES

To simulate electrostatic fluxes that might be placed on surfaces lining cavities on space vehicles, one should assume that the whole surface is held to ground while the cavity is exposed to a 3.5° wide electron beam. Since as was also shown in the text, the ions can be deficient in the classical "loss" cone, we take as a limit, no ions at all. Then we can use the work cited earlier (reference 20) for typical and worse cases.

(1) Typical

Flux = 2×10^9 electrons/cm^2 sec

E = 220 eV .

(2) Worst Case

Flux = 3.5×10^8 electrons/cm^2 sec

E = 2200 eV .

The user is warned that the statistics on the occurrence of these field-aligned fluxes is still poor. The numbers above are based on 20 events. The second event was named as worse case because of the higher energies. A more conservative approach might be to assume both the higher flux and higher energy occur simultaneously even though this has not been observed.

3. USE OF THIS MODEL

The numbers presented in this appendix are not meant to represent an environmental specification in any final sense. They are meant to give typical and maximum fluxes that might reasonably be expected so that designers can at least make a start without utilizing a full computer simulation. Special events such as rapid flows, waves, or fluxes of heavy ions will be considered in the more developed models to follow.