INSTITUTE FOR SPACE STUDIES

Research Reports

(July 1, 1964-June 30, 1965)

GODDARD SPACE FLIGHT CENTER

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Prepared and edited under the direction of Nicholas Panagakos, Public Information Officer

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I. INTRODUCTION

The Goddard Institute for Space Studies is a New York office of the NASA Goddard Space Flight Center. The Institute conducts research in astronomy and geophysics with emphasis on nucleosynthesis, stellar structure and evolution, the origin and development of the solar system and solar-terrestrial relationships. The program also includes basic studies in atmospheric dynamics and theory of turbulence, convection and radiative transfer.

Collaboration with universities in the New York area is an important element in the Institute program. Several universities offer graduate programs of instruction and research in fields related to the activities of the Institute. Institute staff members participate in such programs by offering courses in space-related subjects and by supervising the research of Ph.D. candidates at Columbia University, New York University, City University of New York, Yale University and Yeshiva University.

II. RESEARCH REPORTS

INTENSE RADIO SOURCES AND QUASARS

A. G. W. Cameron

One of the current problems in astrophysics is to account for the large energy releases taking place in galaxies containing intense radio sources and in the new objects described as quasars, or quasi-stellar radio sources. The energy requirements in these sources usually exceed 10^{60} ergs, or a million times the rest mass of the sun. One of the most efficient forms in which this energy might be supplied is the gravitational potential energy release which accompanies the collapse of supernovae. Consequently, it was suggested in a paper entitled "Star Formation in Elliptical Galaxies and Intense Radio Sources," A. G. W. Cameron, Nature, 194, 963, 1962, that the energy requirements might be supplied if there were a nearly simultaneous formation of a very large cluster of stars, many of which would be massive enough to become supernovae. This simultaneous formation would be accomplished by means of a magnetic field contained in the gas in a giant elliptical galaxy or in some other region where the magnetic energy would provide the principal internal energy tending to expand the gas being drawn together by gravitational forces. This magnetic field would thus tend to prevent the fragmentation of the gas into stars until the very late and presumably flattened region of contraction had been reached. Because massive stars have essentially the same lifetime, a simultaneous birth would result in the more massive of the stars reaching the end of their evolutionary tracks within a million years or so. This would meet the requirements on the energy release that would take place during a period of 10^7 years or less. These ideas were further discussed in a paper entitled "Role of Turbulence in Star Formation in Elliptical Galaxies," Nature, 196, 881, 1962.

These ideas were intended to be applied to problems of intense radio sources, and they were put forward before the essential nature of quasars became known. It then became apparent that similar energy problems would arise in quasars, and that amounts of mass of the order of 10^8 solar masses or more would have to become associated with dimensions of only a few parsecs. The idea that the shining gas in quasars might be associated with the large amount of mass again in the form of a cluster which had formed simultaneously was applied to the problem of the light outbursts observed in the quasar 3C273. These light outbursts were much stronger than ordinary supernovae and lasted for a period of 2-4 weeks, thus indicating that dimensions much smaller than that of the quasar itself were involved. Consequently, in a paper entitled "Enhancement of Light Output from a Supernova," by S. A. Colgate and A. G. W. Cameron, Nature, 200, 870, 1963, it was suggested that the explosion of a massive star could result in much greater than normal output providing the star was surrounded by circumstellar gases. The interaction of the supernova shock wave with the circumstellar gases was investigated, and it was found that a good fraction of the kinetic energy of the expanding gases could be converted into visible light if the circumstellar gases had a density of about 10 particles per cubic centimeter. This is in essential agreement with the density of the glowing gas in 3C273 later found by Greenstein and Schmidt.

QUASARS

R. Stothers

A theory of quasars (quasi-stellar radio sources) as cosmic explosions representing the continuing creation of primordial matter was proposed (Nature, 206, 82, 1965). In a steady-state cosmology, the expanding universe must be continually replenished with matter. It is proposed that creation occurs in massive bursts, corresponding to local formations of the ylem of evolutionary cosmology, but on a scale of galaxies or even galaxy clusters. Consequently, creation takes place in a quasi-steady state. It is postulated that (1) matter is created where it is lacking (between galaxy clusters) because it is lacking (due to the universal expansion), (2) quasars are the manifestation of such creation, and (3) matter is created sharing the universal expansion. A variety of phenomena may apparently be explained with this picture, including mass loss from the universe, observational characteristics of quasars, primordial element abundances, galaxy formation, and possibly the clusters of radio galaxies. The details of this proposal will be published separately (M.N., in press, 1965).

GALACTIC EVOLUTION

A. G. W. Cameron

In collaboration with C. J. Hansen and J. W. Truran, evolutionary history of the galaxy has been studied. The main incentive in doing this was to determine how the ratio of helium to hydrogen in the interstellar medium would vary as a function of time. The basic problem is that the present rate of conversion of hydrogen to helium in the stars in the galaxy, as judged by the total stellar luminosity of the galaxy, is inadequate by one order of magnitude to account for the formation of helium in the interstellar medium and in newly formed stars. It had generally been assumed that the enhanced stellar luminosities required to account for the helium might be obtained during the early history of the galaxy when larger numbers of massive stars would be evolving. However, recent studies of stellar evolution, principally by Hayashi, have shown that the more massive stars contain only a very small amount of helium between hydrogen and helium burning shells in their advanced stages of evolution. Consequently, not much helium can be made available to the interstellar medium when these stars explode.

The study was basically exploratory because of the large number of assumvtions necessary. It was necessary to assume a relationship between the luminosity and, the mases of the stars and their times of evolution on the main sequence, as well as on the basic birth rate function, or relative numbers of masses of the stars which are formed at any one time. It was also necessary to extrapolate the trends of some current studies of stellar evolution to determine what the mass fractions of hydrogen, helium and heavier elements would be that are ejected into the interstellar medium from each of the different stellar masses, and how much of the mass would remain behind as a stellar remnant of some kind. Basically, the Salpeter birth rate function was assumed, and the relationships between mass, luminosity and lifetime were closely based upon observation. The main adjustable parameter used to generate various models of galactic history was the prescription for the fraction of the mass of the galaxy which is in the form of gas at any time.

A variety of such models was chosen, and they all led to the following general conclusions. The amounts of helium in the sun and in the more recently formed stars can be accounted for only if the helium content of the interstellar medium comes principally from stars with masses not very different from that of the sun. It follows immediately that the galaxy must have a rather great age, with values of at least 2×10^{10} years being indicated. All of this is based upon the principal initial assumption that the galaxy was initially wholly composed of hydrogen. If some alternate source of initial helium could be found, then such large galactic ages would not be necessary.

The abundances in the interstellar medium of some of the longer lived radioactivities were also followed during these calculations. It was found that the uranium and thorium isotopes have very nearly the abundances deduced for the primitive solar system for a period of many billions of years around the time at which the helium content of the interstellar medium has the solar value. This is a satisfactory check of the self-consistency of the models of galactic history, but at the same time it also indicates that many of the attempts which have been made to deduce something about the ages of element formation by means of these cosmo-chronological calculations are not very meaningful.

These results have been reported in a paper entitled "The Helium Content of the Galaxy," by J. W. Truran, C. J. Hansen and A. G. W. Cameron.

SOLAR AND STELLAR EVOLUTION

D. Ezer and A. G. W. Cameron

The early work on the early evolution of the sun was published under the title "The Early Evolution of the Sun," Icarus, 1, 442, 1963. In the work reported in this paper, the evolution of the sun was studied by conventional methods in which the equations of stellar structure were integrated inwards from the surface and outwards from the center to a common matching point. The energy source was entirely gravitational, and it was assumed that each model was contracting in a locally homologous manner. Particular attention was paid to the problem of obtaining satisfactory surface boundary conditions, since much of the intent of this early investigation was to test the validity of the ideas of Hayashi that the sun would be highly luminous and completely convective during its early evolutionary stages.

The results fully confirmed Hayashi's ideas. The early sun was found to be fully convective and highly luminous. It was found that the threshold of stability for the sun, in which the released gravitational potential energy is just sufficient to supply the internal thermal energy as well as the dissociation and ionization energies of the hydrogen and helium in the model, occurred for a radius of the order of 60 times the present solar radius. The time required to approach the vicinity of the main sequence was a few million years, although this time could not be determined very precisely owing to the fact that nuclear sources were not included in the calculations. The principal objective was to find some indication of the lifetime in the early, more highly luminous stages, which were found to be less than a million years.

This early work was followed by more detailed considerations on the evolution of the sun. The method of calculations was changed to that of Henyey, in which the model is broken up into a large number of spherical mass zones, and the equations of stellar structure are solved at the zone boundaries. As in the earlier calculations, a composition of the sun was assumed, based on evidence in meteorites and in the O and B stars. In this composition, about 1/3 of the solar matter was hydrogen and nearly 1/3 was helium. The opacity of this material was calculated using the Los Alamos Opacity Code. The convection theory used in the calculations was that of Bohm-Vitense, in which the possibility of having superadiabatic temperature gradients was taken into account. The main uncertainty in using such convection theory is knowing what to use for the mixing length of the gas elements. It was originally intended to choose two values of the mixing length, which were taken as one and two times the pressure scale height, and to interpolate between the results to find which pressure scale height should be used.

The subsequent calculations of stellar evolution showed that the sun started with a high luminosity and was fully convective, as was to be expected, and that after becoming largely radiative in the interior it moved to the left in the H-R diagram, but the luminosity remained much too high throughout the solar evolutionary history to allow the sun's position in the H-R diagram to be fitted. The main difference due to the different mixing lengths was a change in the surface temperature of the sun, but the luminosity was found to be nearly independent of the mixing length.

It was thus considered likely that the composition used for the sun was in error. At about this time in the investigation, the results of the Goddard rocket flight were published in which the relevant abundances of heavier solar cosmic rays had been determined. These results were used to re-determine the abundances of helium and neon in the solar composition; the results showed that the sun should be composed of approximately 3/4 of hydrogen and only 1/4 of helium. When the evolutionary calculations were again performed, it was found that very nearly the present luminosity of the sun was obtained after an evolutionary time of 4.5×10^9 years. Furthermore, it was found that the track calculated with the mixing length set equal to two pressure scale heights passed very close to the present position of the sun in the H-R diagram. Consequently, this value of the mixing length was adopted for further calculations in stellar evolution. These results are reported in a paper entitled "A Study of Solar Evolution," by D. Ezer and A. G. W. Cameron.

These techniques have been extended to a computation of the early stages of the evolution of stars of other masses. The stars considered have included the following masses, in units of the solar mass: 0.1, 0.2, 0.5, 0.7, 1, 2, 5, 10, 20, 50 and 100. In nearly all of these cases satisfactory evolutionary tracks onto the main sequence have been computed, and many details of the behavior of the interior structures of the stars have been studied. It is found that all stars in the early stages of evolution have passed through a stage in which they are fully convective. The higher mass stars form a radiative core at relatively a much earlier stage than the lower mass stars, and they then have quite long, roughly horizontal tracks in the H-R diagram before settling down onto the main sequence. In general there is good agreement with somé similar calculations carried out by Iben over a much more restricted mass range, with certain deviations in the track position being attributable to the fact that Iben did not use opacities as sophisticated as those available in the Los Alamos Opacity Code. Before the results for the lowest masses are completed, it will also be necessary to decide how to treat the problem of pressure ionization of the material. The density is sufficiently high at the center of these objects, and the temperature sufficiently low, that the conventional ionization formulas are not fully applicable.

One point in connection with solar evolution to which particular attention has been paid in our investigations concerns the abundance of lithium. Lithium in the sun is reduced in abundance relative to chemically similar elements in the earth and meteorites by more than two orders of magnitude. Our solar evolutionary tracks do not indicate that lithium should be destroyed by nearly so great a factor; a factor of a few tens per cent or a factor of two seems to be more what is indicated. Investigations have been carried out by Mr. Robert Stein to determine whether additional lithium depletion can be expected as a result of penetrative convection at the base of the outer convection zone in the sun. However, it has been found that no significant increase in lithium destruction can occur by this process. An investigation was also carried out to see whether further lithium depletion would result if the basic gravitational theory should be a combination of vector and scalar gravitational fields. In such a theory, the basic gravitational constant would vary with time. Dicke has provided a prescription for the type of variation that he would expect. The effect of the varying gravitational constant upon solar evolution was investigated and a track was found which progressively decreased in luminosity as the sun became older. However, it was found that there is less lithium depletion in this alternative form of solar evolution than there is in the one previously calculated. At present, consideration is being given to the effects on lithium depletion of circulation currents in the sun related to its rotation and to the effects of mass loss in the early history of the sun.

Mr. Stein is also investigating the effects of turbulence in the transition layer of the sun on the generation of acoustic and gravity waves. In this he is generalizing a theory of the generation of sound by turbulence due to Lighthill, the principal effect of generalization being the inclusion of the effects of the stratified atmosphere. He has found that in the stratified atmosphere turbulence will generate both acoustic and gravity waves, and that the efficiency of this generation is strongly related to the ratio between the eddy size and the scale height of the medium. There are at present some questions on the correlation of velocities in the turbulent elements which need to be resolved before the theory can be put into final form. Mr. Stein hopes to apply this theory to the generation and propagation of these waves in the sun and to see how much of the heating of the chromosphere and corona can be attributed to this mechanism. The general objective here is to try to account for the heating of the chromosphere and corona of the sun and to apply this theory to the heating of the chromosphere and corona about other stars or about the sun during its early evolutionary history. This would then allow a crude calculation of the rates of mass loss in other stars and in the earlier history of the sun.

STELLAR EVOLUTION

R. Stothers

The consequences of substituting the $\mathfrak{M}$-L-μ (mass-luminosity-mean molecular weight) relation of stellar structure theory in place of the "empirical" $\mathfrak{M}$-L and $\mathfrak{M}$-μ relations were investigated for the Russian theory of evolution of completely mixed stars with mass loss. (M.N., in press, 1965). In this scheme, the mass loss rate becomes a free parameter, but stars still evolve along the main sequence. It is found that by theoretically evolving the initial luminosity function, the observed luminosity functions of early-type galactic clusters may be reasonably well reproduced with a variety of mass loss rates and ages. Hence the luminosity function per se does not give definite evidence for the mode of stellar evolution (homogeneous or inhomogeneous), rate of mass loss, or age of a cluster. The numerical computations involved in this problem were carried out by a student assistant, Mr. Blair Savage.

In an extension of preliminary theoretical calculations on β Cephei stars, which appeared in the author's doctoral dissertation (Harvard University, 1963), an attempt has been made to explain the β Cephei variables as non-rotating stars undergoing radial oscillations on the basis of their relatively low observed rotational velocities and the period analysis by van Hoof (Ap.J., 141, 671-687, 1965). Arguments based on the central condensation and on the time scale of evolution vis-a-vis their observed numbers indicate that these BO.5 - B2 giants are in the hydrogen-burning phase. Model sequences are constructed for stars of 15 and 20 $M_\odot$ to the end of hydrogen-burning. The pulsational characteristics are then obtained by perturbing the stable models in the usual adiabatic approximation. The results show that at some central hydrogen abundance which is higher for the lower masses, the periods and their ratios may be accounted for. Ideally, these quantities imply a unique mass and mean molecular weight for each observed star on the H-R diagram, but comparison of theory and observation gives at present merely a mass range of 10-20 $M_\odot$ and probably a "normal" chemical composition. At any rate, the hypothesis of evolution of main sequence 09-B1 stars across the instability strip seems to be correct. Uncertainties in the semiconvective theory of massive stars would appear to be irrelevant, since the quasi-stable zone has almost no effect on the pulsational eigenfrequencies. Several lines of observational evidence tend to confirm the theoretical results that β Cephei stars of lower mass fall closer to the initial main sequence. The Wolf-Rayet objects form an apparent extension of the instability strip to higher masses (O stars).

During the fall and winter of 1964-65, the theoretical evolution of a star of 30 $M_\odot$ was calculated beyond the phases of hydrogen burning and the subsequent gravitational contraction. The evolution was considered during the phases of helium ignition (I), depletion (He), and exhaustion (X) (Ap.J., 143, in press, 1966). After the brief I-phase (1.5×10^4 years) during which the onset of helium burning halts the gravitational contraction in the core, helium is depleted in a large convective region growing outward in mass fraction until it nearly overtakes the hydrogen burning shell. Helium depletion causes a radius shrinkage until $Y_c = 0.3$, whereupon the radius re-expands. The final C^{12}/O^{16} ratio in the core is uncertain, but will be zero if the critical reduced alpha width in O^{16} is greater than 0.3. The luminosity of the hydrogen shell source is low and monotonically decreases, even though the shell finally reaches the hydrogen-rich, semiconvective zone ($\Delta X = 0.15$) when $Y_c = 0.01$. The star covers the spectral range from B1 to B8, while semiconvection maintains the total luminosity at a nearly constant value. The lifetime of the He-phase is 5.2×10^5 years. During the X-phase (1.3×10^4 years), the carbon-alpha reaction is able to sustain the luminosity in the shrinking convective core until $Y_c = 10^{-4}$. Thereupon the gravitational contraction in the core dominates the nuclear sources, and rapidly (10^3 years) brings the star into the region of late-type supergiants. The weak shell burning, prolonged by hydrogen enrichment due to full convective mixing at the inner boundary of the semi-convective zone, will then be extinguished by the envelope expansion. Since the new convective zone (along with the semi-convective zone) eventually retreats toward the surface, leaving behind a radiative zone of frozen composition, two major fixed composition discontinuities occur in the star: hydrogen-helium ($q = 0.44$) and helium-oxygen ($q = 0.37$). The evolutionary features of very massive stars are discussed generally, and a rough time scale computed for the very late phases with and without neutrino emission. In either case, the total lifetime to iron core formation will be slightly less than 6 million years.

Work was continued on the details of the evolutionary phases, during the winter and spring of 1965. Models up to the onset of oxygen burning and the possible modes of evolution were studied. The results have not yet been completely analyzed.

NEUTRINOS IN STELLAR STRUCTURE

Hong-Yee Chiu

The later stages of stellar evolution, when the internal temperature is above 10^9 °K, are affected by neutrino processes. Under these conditions, neutrino emission occurs at a rate higher than photon emission. It is found that the homology relation (Density) ~(Temperature)^3 breaks down completely, and that in general the density rises much faster than the third power of temperature. In regions where nuclear burning commences (C^{12}-O^{16} or O^{16}-O^{16} reactions), the interior stellar structure is determined by the following condition: (Nuclear Energy Production Rate) + (Neutrino Energy Dissipation Rate) = 0. Such curves have negative power dependence on temperature ($\rho \sim T^{-12}$) or are isothermal. The rapid removal of energy from the core of the star results in a short time scale for these stages and the star continues to contract. The stars evolve (independently of their mass) to a very high central density (~10^{9-10} g/cm^3) at a rather low central temperature (~3-4 $\times 10^9$ °K).

Neutrino processes strongly influence stellar evolution in their later stages. Neutrinos are produced in various stages of stellar evolution, but they are most important when the star becomes a supernova. Although in most cases the neutrino escapes, under extreme density conditions ($\rho \gtrsim 10^{11}$ g/cm^3) the absorption of neutrinos by stellar matter may also become important (Chiu 1964). The production of neutrinos is taken into account easily by including it in the energy production term, and we have:

$$\varepsilon = \varepsilon_{gr} + \varepsilon_n + (dU/dt),$$

where ε is the total energy production rate, ε_{gr} is the rate of gravitational energy release (in ergs/g-sec), ε_n the rate of nuclear energy release, and (dU/dt) is the rate that energy is dissipated by neutrino emission.

When the rate of photon energy transfer exceeds the rate of neutrino emission, neutrinos dominate the course of stellar evolution. The photon opacity κ_{ph} of stellar matter is always greater than $\kappa_e = 0.19$ cm^2/g (the opacity for electron scattering). The mean free path of photons is roughly ($1/\kappa_e$) in g/cm^2, and hence, is always shorter than 5 g/cm^2. The luminosity of a star apart from a numerical factor which is not very different from unity is roughly

$$L \approx \frac{\text{(Photon Energy Content of the Star)}}{(R/c) \cdot (R/\lambda)},$$

where R is the radius of the star and c is the velocity of light, and λ is the photon mean free path (in cm). The relaxation time for a star to be cooled by photon emission τ_{ph} is therefore

$$\tau_{ph} = \frac{\text{(Photon Energy Content of the Star)}}{(L)} = \frac{R^2}{c\lambda}.$$

Using a simple model in which the temperature T and the radius R are related by the following condition (which is derivable from the virial theorem)

$$-(\text{Gravitational Energy}) = \tfrac{1}{2}(GM^2/R = (3/2)R_g T\, M = (\text{Thermal Energy}),$$

we find $\tau_{ph} = 2 \times 10^{11}\, T_9$ sec. The corresponding relaxation time via pair annihilation neutrino emission τ_ν is $\tau_\nu = \mathcal{E}/-(dU/dt) = 1.5 \times 10^4 \exp(11.9/T_9)\, T_9\, (\odot/M)^2, T_9 \ll 6$. At $T_9 = 1$, $\tau_\nu = 2 \times 10^7$ sec and $\tau_{ph} = 2 \times 10^{11}$ sec. Hence, we can conclude that at $T_9 \gtrsim 1$ the photon energy transport process cannot be important in the center or stars.

Soon after the temperature exceeds $\sim 10^9$ °K the rate of energy dissipation by neutrinos will dominate over the photon processes. Thus, there exist only narrow temperature-density regions where one must consider both photon and neutrino processes simultaneously. Outside this region one can either completely neglect the photon energy transfer process (except for luminosity calculations) or completely neglect the neutrino processes. We shall define a star to be a photon star if the major part of the energy loss of the star is through surface emission, and a neutrino star if the major part of the energy loss is through neutrino emission.

The idea of a neutrino star is only an abstraction: in real stars the surface temperature is between 10^3-10^5 °K; thus, in the outer region of a star, photon processes must dominate. However, the neutrino active core will evolve rapidly before the outer region can effectively affect the core's structure (e.g., by the addition of mass to the core, or the addition or removal of energy from the core). Thus, the concept of a neutrino star is helpful in determining the evolutionary properties of a star in its later stages.

The energy sources of stars are either gravitational or nuclear in origin. Nuclear reactions occur at well defined temperatures, and when nuclear energy is not available the star must contract to supply the energy lost via neutrino or photon emission.

The evolution of a 2 solar mass star is shown in Figure I. Note that if the star evolves homologously, this line will be displaced without distortion along a line of slope 3 (Figure 2). The actual evolution of the star is very complicated, as indicated in Figure 1.

Because of the extremely rapid cooling by neutrino emission, there is a positive temperature gradient in the core of the star and in the maximum temperature. Thus, nuclear burning occurs in a shell surrounding the core, and the core continues to collapse with $\rho \sim T^8$ until nuclear burning begins. The final collapse state will be at a very high density ($\sim 10^{9-10}$ g/cm^3) and at a much lower temperature ($\sim 3 - 4 \times 10^9$ °K).

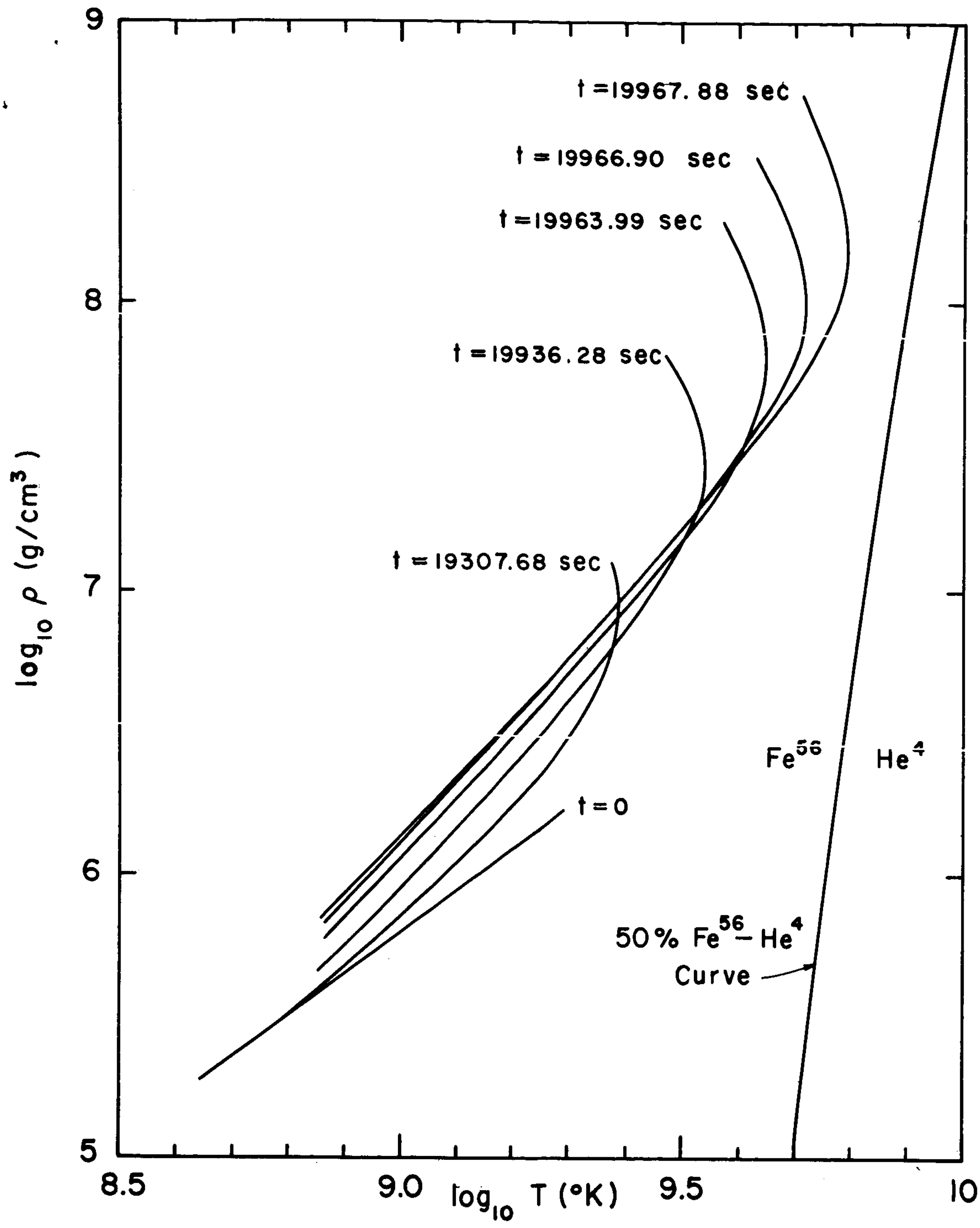


Figure 1: The evolution of neutrino stars. The structures at various times are shown. The highest density point on each curve is the center of the star. Although t is given to 7 decimal places only the time differences between stages are useful numbers. In this model the collapse condition is obtained at $\rho \sim 10^9$ g/cm^3 while the star is still composed of iron. This model demonstrates the complete breakdown of the concept of homologous contraction in neutrino stars.

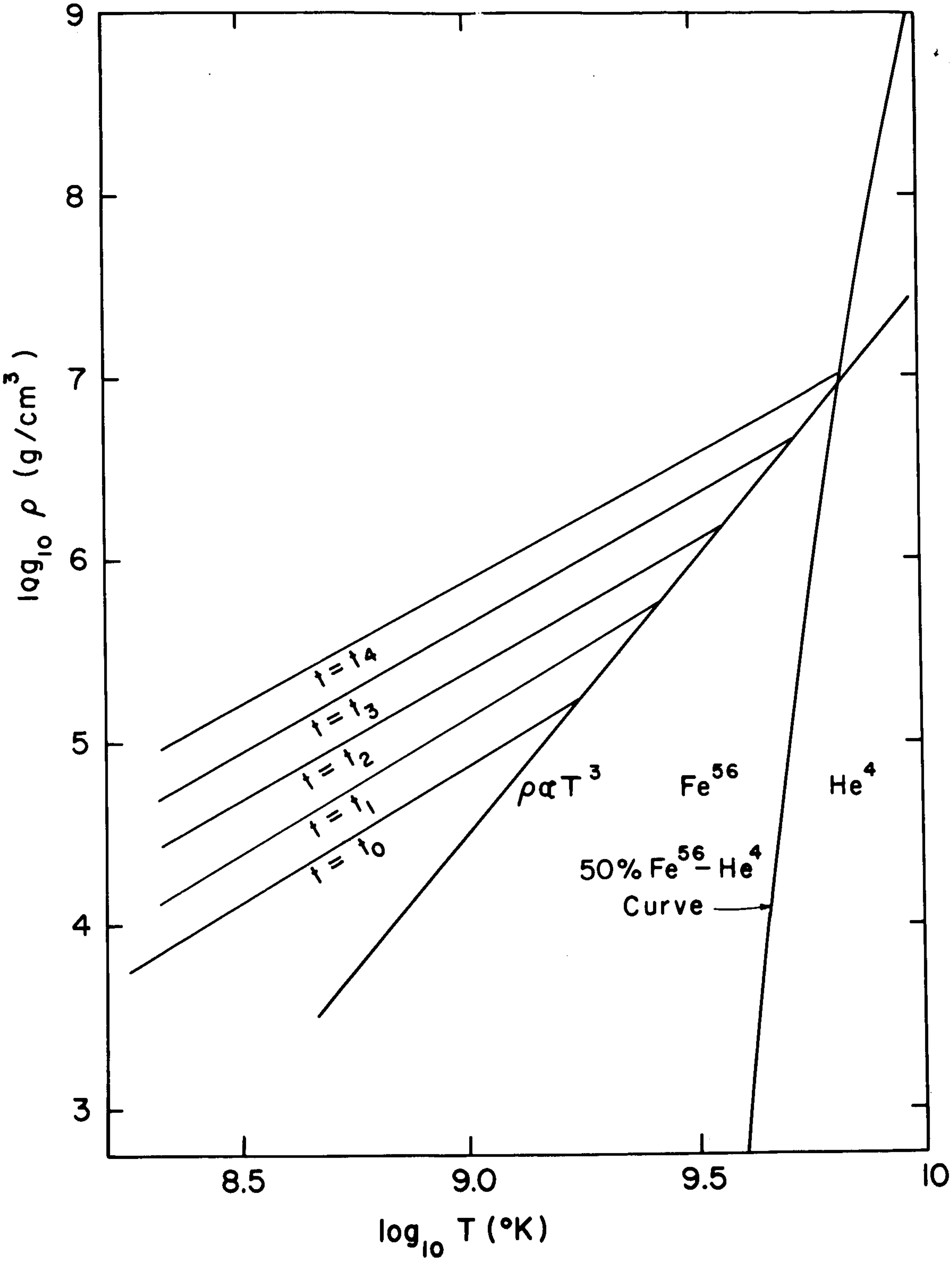


Figure 2: the evolution of stars under homologous contraction hypothesis.

PLANETARY NEBULAE

Hong-Yee Chiu
(with C. W. Chin)

It is now established that the central star in a planetary nebula has a very high surface temperature and is in a process of evolving into a white dwarf. The surface temperature is of the order of 2×10^5 °K and the luminosity is about $10^4 L_\odot$. The estimated mass is approximately $1_\odot$ (solar mass). This gives a radius of about 0.07 times the radius of the sun ($R_\odot$), and an estimated interior temperature a few times 10^8 °K. The life time of a planetary nebula as established from data on mass ejection is approximately $1_\odot$. Since the radius of a white dwarf is about 0.01 $R_\odot$, the structure of the central star differs drastically from that of a white dwarf.

We have calculated the evolution of the central star, assuming that it is a hot white dwarf. During evolution, the surface temperature is almost a constant, but the radius decreases. The luminosity as well as the central temperature decreases. The life time at each stage can be computed, assuming only photon emission. The life time progressively increases as the star cools, from 2×10^4 years at the planetary stages (with a luminosity of $10^4 L_\odot$) to 10^6 years when the luminosity is about $10^{2-3} L_\odot$. This is in contrast to observation, where only white dwarfs and planetary nebulae have been observed, but no stars in the luminosity range $10\text{-}10^5 L_\odot$. It seems that the central star evolves quickly through the intermediate luminosity range.

By including the neutrino emission process (plasma neutrino), it was found that the life time in the intermediate stage is drastically reduced from 10^6 years to less than 10^4 years. This would indicate that there are very few stars in the luminosity range $10\text{-}10^3 L_\odot$ and that the planetary nebula apparently ejects only a small amount of mass in the intermediate stage. A detailed report is under preparation and will be submitted for publication soon.

SUPERNOVA EXPLOSIONS

A. G. W. Cameron

In an effort to determine what strength of supernova shock wave should be encountered by various composition regions, an investigation is being made of the hydrodynamics of these explosions. This is being done by D. Arnett. In the hydrodynamic calculation it is necessary to divide a stellar model into many spherical mass zones, and to solve the hydrodynamic equations at the boundaries of these zones as one advances the time. It is necessary to pay special attention to the Courant condition which makes the time steps sufficiently small so that sound cannot communicate across a zone during a time step. A variety of initial models are being considered which are being made unstable at the center, either due to the lowering of the pressure by nuclear conversion of iron to helium, or by lowering the pressure by electron capture on the elements that are present. Typically, during the resulting implosion a core will start to build up having approximately nuclear density or a little greater; the material continuing to rain down on this core will release a great deal of heat due to the gravitational potential energy release. This energy would rapidly be radiated away from the interior of the star emission of neutrino-antineutrino pairs, were it not for the fact that neutrino scattering on electrons makes the interior opaque to the escape of neutrinos. Thus, the neutrinos play a role in transporting energy out from the core to the descending material. Because of the heating of this descending material, a shock wave forms and starts to progress outward. However, when the shock wave emerges from a region of density in the vicinity of 10^{11} grams per cubic centimeter, it has a temperature of 2×10^{11} °K. At lower densities the neutrinos emitted from the shock wave region escape from the star and no significant energy transfer takes place. Consequently, the calculations so far have shown that the shock wave will die away at this point in the star.

Thus, the main problem of the supernova dynamics appears to be the transfer of energy from the interior to the descending material in a way sufficient to form a shock which can reverse this inward flow and throw off the material, as observed to take place in nature. At present an investigation is being made of the manner in which such energy transfer by neutrinos should be put more efficiently into the mode. Investigations are also being made to see whether additional sources of neutrino opacity may have been overlooked.

NUCLEOSYNTHESIS

A. G. W. Cameron

A variety of problems in the general area of nucleosynthesis have been under investigation recently. These have generally centered around the problem of the behavior of nuclear abundances at high temperatures, where there is a fairly rapid emission and absorption of nucleons from nuclei by photodisintegration and reabsorption processes, and the problems of neutron capture among the heavy elements, both on slow and fast time scales. In order to investigate some of these problems it has been necessary to improve current theories of the statistical properties of nuclei.

The first of these properties is the nuclear mass. Some years ago, A. G. W. Cameron concluded that the yields of heavy uranium nuclei formed in the Mike thermonuclear explosion of 1952 were inconsistent with the mass surface as it exists in conventional mass formulae based upon the von Weizsacker formulation of atomic masses. The principal direction of departure from the conventional mass formula would have to be that the neutron binding energies of the more neutron rich isotopes should not decrease as much as a conventional mass formula demanded. The problem has been to find how the mass formula should be modified in order to incorporate these effects. In some work done with the assistance of Mr. Richard Elkin, it has been found that the only reasonable way to obtain this effect seems to be by modification of the way in which symmetry energy correction terms are put into the mass formula. In effect, the parabolic dependence of the symmetry energy in the vicinity of those nuclei where the number of neutrons is equal to the number of protons should be expected to fail when the number of neutrons becomes greatly different from the number of protons. Consequently, the symmetry energy term needs to have some higher energy terms included in some way. This has been done in an effective way, which does not demand any additional basic constants to be determined, by changing the form of the basic mass equation so that it contains an exponential term in the symmetry energy. The modified mass formula may thus be referred to as the exponential form of the mass formula. It was found that it fitted masses near the valley of beta stability just as well as the conventional mass formula does, and, furthermore, it requires that neutron binding energies fall off much less rapidly in the neutron rich region than is true for the conventional mass formula. Empirical shell and pairing correction terms were found as a function of neutron and proton numbers for inclusion in this formula and have proved to be of use in subsequent investigations, as will be seen below. This work has been reported in a paper entitled "Role of Symmetry Energy in the Atomic Mass Formula," by A. G. W. Cameron and R. M. Elkin.

It has also been necessary to improve our knowledge of nuclear level densities, since nuclear reaction rates are particularly sensitive to these. In a conventional mass formula of the type that may be derived from a Fermi-gas model of the nucleus, the level densities can be expected to increase essentially as exp const. $E^{1/2}$, where

E is the excitation energy. One has every expectation that this should be the basic form of the level density formula at high energies. Nevertheless, at low energies it has been found that directly observed level densities can be better accounted for by a formula of the type exp const. E. In some work done to a small extent in collaboration with F. S. Chen, but principally with A. Gilbert, it has been shown that the latter form for the level densities is much to be preferred in a low lying region of excitation. A composite level density formula has been constructed in which the low energy and high energy forms of the formula are fitted tangentially. The constants which appear in these formulae have been determined, making use of the empirically determined shell correction term of the mass formula. The resulting composite level density formula has been found to fit level densities with a fairly high degree of reliability, root mean square error factors of the order of 1.75 being found among the heavier nuclei region. This work has been reported in two papers entitled "Level Densities in Lighter Nuclei," by A. Gilbert, F. S. Chen and A. G. W. Cameron, and "A Composite Nuclear Level Density Formula with Shell Corrections," by A. Gilbert and A. G. W. Cameron.

Nuclear radiation studies have also been investigated by C. J. Hansen in collaboration with A. G. W. Cameron. In constructing a radiation width formula it is necessary to integrate the dipole radiation toward all lower lying levels, and to divide by the level density in the region of the radiating level. The resulting radiation widths must be normalized through the determination of some common scaling factor, but when this is done it is found that satisfactory predictions of radiation widths can be made. There is some scatter of the ratios of observed to predicted widths in a characteristic pattern that correlates well with the neutron strength functions for deformed nuclei. This correlation is not unexpected theoretically, but introduces only a few tens of percent variation in the constant, and thus for practical purposes it can be neglected.

These various nuclear functions have been amalgamated into a general code for calculating nuclear reaction rates by Mr. J. W. Truran. It has been found that the formula predicts observed reaction rates generally to within a factor of two, providing the excitation energy is not too great. In particular, it is found that the neutron capture cross sections of heavy uranium isotopes as computed based upon the exponential mass formula gives cross sections consistent with the yields of the Mike thermonuclear explosion, whereas that based upon the conventional mass formula do not.

The reaction rate code has been used to compute a very large number of reaction rates for emission and absorption of neutrons, protons, alpha particles and photons in a complex network of reactions which is involved in the approach of nuclei toward the condition of statistical equilibrium. The resulting nuclear reaction network is being relaxed under a variety of conditions. Mr. A. Gilbert is considering the rates at which a system composed initially of silicon 28 will relax toward nuclear statistical equilibrium about iron 56. The key reactions here are the photodisintegration of the silicon 28, but the system relaxes by at least 2 orders of magnitude more slowly than this photodisintegration owing to the fact that the silicon 28 is to a very great extent replenished when the emitted particles are recaptured on their products. J. W. Truran is investigating the changes in nuclear abundances which take place when a supernova shock wave passes over nuclei of various composition. With a shock wave peaking near 5×10^9 °K, he is finding that the initial composition of silicon 28 will change substantially into nuclei in the iron region during the passage of the shock wave. It is intended to investigate the behavior of many other nuclear regions also.

Investigations have also been carried out on neutron capture problems. The abundances of the elements as determined in the sun and in meteorites were re-examined critically, and a new abundance table of the elements was constructed. From this, abundances of those nuclei formed predominantly by neutron capture taking place on a slow time scale were determined or estimated. These abundances were combined with neutron capture cross sections measured at the Oak Ridge National Laboratory to determine the fundamental curve of abundance times cross section, which has a value monotonically decreasing with mass number. An investigation has been carried out to find under what conditions of neutron source this curve can be reproduced. The initial composition was assumed to be essentially that of the sun, and the principal sources of neutrons were considered to be the reaction Ne^{22} (α, n) Mg^{25}, and the reaction C^{12} (C^{12}, n) Mg^{23}. It was found that the observed build-up to the abundances of lead and bismuth can only be accounted for if most of the uncertain quantities in the calculation are given rather favorable values. It was also found that the distribution of integrated neutron fluxes in the source material can be chosen in quite a variety of ways in order to reproduce the observed effects. The optimum distribution of these integrated neutron fluxes has not yet been determined.

A program of study of the neutron capture taking place on a fast time scale is currently under way. In this program, the new techniques for calculating nuclear reaction cross sections are being used to determine neutron capture cross sections for very neutron rich nuclei, and also the beta decay probabilities of these nuclei are being determined by integrating beta decay transition probabilities over the wide variety of excited states in the daughter nuclei taking account of neutron emission from the excited states.

NEUTRON STARS AS X-RAY SOURCES

Hong-Yee Chiu

The existence of neutron stars was first proposed in 1931, and a theory of its interior structure based on the theory of general relativity was later developed. The density of neutron stars is about 10^{14} g/cm^3, with a typical radius of 10 km. At such high density, the Fermi energy of electrons is of the order of a few hundred mev and nuclei cannot exist; the gas is composed mainly of neutrons. The neutron star is thought to be a remnant of supernova processes. Formed at a temperature $\gtrsim 10^{10}$ °K, it cools to ~ temperature of about 5×10^8 °K in a matter of a few weeks via neutrino processes. Henceforth, the loss of energy is through surface black body emission, with a luminosity in the range 1 $L_\odot$ to 10^3 $L_\odot$. This corresponds to a surface temperature of $10^6 \rightarrow 10^7$ °K, and most energy is in the wavelength band 1Å → 10Å. Neutron stars are therefore potential cosmic x-ray emitters, if they exist.

There are uncertainties in the theory, primarily stemming from the neutrino energy loss rate. John Bahcall and Wolf suggested a neutrino process, which, if applicable to the density region of stable neutron stars, would imply that the surface temperature of a neutron star is below 10^5 °K and hence would not penetrate the interstellar medium. At present, uncertainties in a nuclear many-body theory preclude a definite statement if this neutrino loss mechanism will operate in neutron stars.

In considering the radiation characteristic of a neutron star x-ray source, one finds that the source ScXR-1 is the most likely candidate. Further measurements on the angular diameter of this source should prove fruitful.

NEUTRON STARS

A. G. W. Cameron

Interest in the possibility that the newly discovered x-ray sources in the sky might be connected with the remnants to supernova explosions that might remain as neutron or hyperon stars led to a new investigation of the properties of such objects. An extensive series of investigations was carried out by S. Tsuruta. Miss Tsuruta commenced by investigating the properties of matter at high temperatures and very high densities in which the usual abundance peak centered about Fe^{56} at low densities is modified by the presence of the high Fermi level of the electrons. It was found that throughout most of the region the peak of the abundances shifts to the vicinity of the closed shell of 50 neutrons. At densities between 10^{11} and 10^{12} gm/cm^3, nuclei are dissolved into neutrons, with smaller amounts of electrons and protons. At still higher densities various hyperons also become present as well as muons and pions.

A composite equation of state was constructed for the range of density spanned by these calculations. It was also desired to investigate what role nuclear forces would play in the equation of state. Accordingly, two forms for the nuclear force interactions were chosen. These were based upon relationships given by Levinger and Simmons for a neutron gas. In both forms the long range attractive forces are similar, but in one of them the short range repulsive forces come in rapidly, whereas in the other the short range forces come in slowly. It was hoped that the use of these two equations of state would span the likely range of behavior of matter with nuclear forces present.

Neutron stars were constructed with these equations of state by solving the general relativistic equations of hydrostatic equilibrium. It was found that the two equations of state give two distinctly different relationships between the mass of the star and the central density. It was found that in the main branch of the curve likely to give rise to stable neutron stars the mass of the configuration rises very rapidly with central density. However, this central density may be anywhere in the range 10^{15} to 10^{16} gm/cm^3, considerably greater than nuclear density. The upper limit of the mass of the stable neutron star probably lies in the range 1-2 solar masses. A variety of interesting observations were made of the calculated properties of the models at still higher central density where they are generally expected to be unstable.

Six models of neutron stars were chosen, three with each equation of state, to investigate the cooling properties. Envelopes of iron and magnesium were fitted to these models, and it was found that there was very little effect due to composition. The envelope must be fitted to such a model by supplementing the equations of hydrostatic equilibrium by equations giving a steady energy flow from the interior to the surface. The opacity of the material was obtained from the Los Alamos Opacity Code. Energy loss by radiation from the surface was included in the calculations as was also energy loss by various neutrino emission processes in the interior. The latter include emission of plasma neutrinos and the emission of neutrinos from the URCA process, in which neutrons and protons are successively transformed into one another. At present energy losses by neutrino emission due to bremsstrahlung are also being included in the calculations.

These calculations show that neutron stars may readily have surface temperatures of several million degrees up to some thousands of years, and of two million degrees at an age of 10^5 years. Thus, they can be candidates for some of the x-ray objects.

Recent observations of the strong x-ray sources in the Crab Nebula and Scorpius have shown that there may be a nonthermal high energy tail to the x-ray spectrum. The Crab Nebula's x-ray source has dimensions of the order of a light year. These observations indicate that if these two objects are to be identified with a neutron star, mechanisms of x-ray emission in addition to simple thermal emission from the surface would be required.

This has led to a new line of inquiry into the properties of radially vibrating neutron stars. Such stars can be quite cold, yet they may store possibly as much as 10^{52} ergs of mechanical vibration energy. This energy may be dissipated in a variety of nonthermal ways. The radial vibrations may generate shock waves near the surface which can heat a circumstellar envelope. This may give rise to a stellar wind, as well as bremsstrahlung corresponding to a high kinetic temperature. If there is a magnetic field embedded in the neutron star, then the vibrations will induce hydromagnetic waves in the field system which should be very effective in accelerating particles, particularly electrons. As the electrons diffuse out of the magnetic field system they may radiate in the x-ray region for periods of up to a year. The x-ray structure of the Crab Nebula may possibly be understood in this way. The ions which would be accelerated in the neutron star magnetosphere may also escape, and, hence, neutron stars may be some of the principal injectors of cosmic rays into the galaxy.

Miss Tsuruta is continuing to investigate the vibrational properties of neutron stars. She has found that models with a variety of equations of state give vibration periods in the range of 0.25 to one millisecond. Mr. Michael Mock is constructing a hydrodynamic code in which he will investigate the vibrations of the neutron stars and the shock wave heating near the surface.

ABUNDANCES IN PECULIAR A STARS

A. G. W. Cameron

Certain stars in the vicinity of spectral class A are described as being peculiar because they have very anomalous abundances of elements on their surfaces. They are usually also observed to have very strong and variable magnetic fields present. The abundance anomalies quite often take the form of very large overabundances of certain heavy elements. However, there are certain specific types of anomalies among the light elements, which usually include a deficiency of oxygen, and overabundances of such elements as silicon, sulfur and manganese. The sources of these abundance anomalies are not understood.

An investigation is being carried out by Peter Brancazio to determine whether abundance anomalies of these kinds may be produced by nuclear surface reactions. In such surface reactions it is envisaged that the bombarding particles may be protons, alpha particles or heavier ions. The protons will have mainly a destructive effect, since the rates of proton capture by radiative emission are very slow, whereas at higher energies, incoming protons will be accompanied by the ejection of several particles. On the other hand, bombardment by alpha particles or heavy ions can build up toward heavier nuclei, since an absorption of an alpha particle or heavier ion may be accompanied by the emission of one or two nucleons, but there is a net gain in mass number.

Mr. Brancazio is computing nuclear reaction cross sections for a wide variety of these reactions using the techniques of the nuclear reaction code which is described above. He has generalized this code to take into account higher energy collisions with accompanying spallation. He will assume energy spectra having the fluxes which fall off with energy, as some power of the energy as is observed to occur in solar cosmic rays.

THE THEORY OF A ONE-DIMENSIONAL SELF-GRAVITATING STELLAR GAS; THE MOTION OF STARS PERPENDICULAR TO THE PLANE OF THE GALAXY

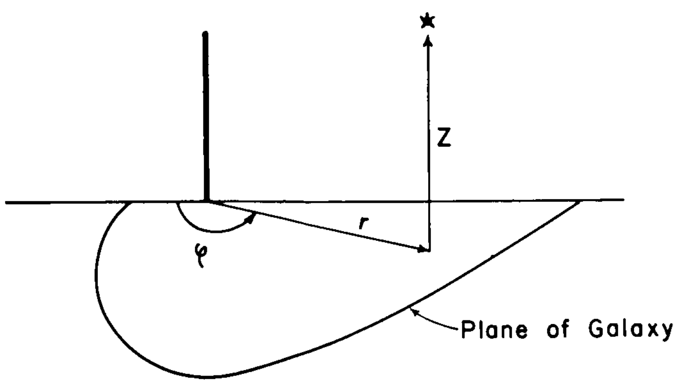
M. Lecar

A restricted but presently unobtainable goal of the theory of Galactic Structure is to obtain a self-consistent dynamical description of a galaxy consisting only of gravitating mass points. This idealized model, neglecting the interstellar gas, hopefully could reproduce the general shape of disk-like galaxies, even though it may fail to reproduce such important observed features as spiral arms. This possibility is bolstered by the observation that 85% or more of the mass of disk-like galaxies is in the form of stars.

On the other hand, since a stellar gas relaxes very slowly, the present shape of the Galaxy may merely reflect the motions of the gas from which the stars were formed, and these motions in turn may have been determined by the viscous, magnetic and pressure forces operable only in the gas. If this is the case, the study of gravitating mass points (Stellar Dynamics) may not lead to an understanding of why the Galaxy is disk-shaped. But, in any case, Stellar Dynamics must be used (since the Galaxy is now mostly stars) to determine how long the Galaxy will remain disk-shaped. Since more than half of the Galaxies are disk-shaped, one suspects that this configuration is stable in a stellar gas.

The usual starting point is to describe a steady state axially symmetric distribution of stellar positions and velocities by means of a Boltzmann-type equation.

In cylindrical coordinates (r, φ, z), where r and φ lie in the plane of the Galaxy, and z is perpendicular to that plane.



Let $f(r, \varphi, z, V_r, V_\varphi, V_z)\, dr \cdot r\, d\varphi \cdot dz\, dV_r\, dV_\varphi\, dV_z$ be the number of stars with $r', \varphi', \ldots v_z'$ satisfying $r < r' < r + dr, \ldots, V_z < V_z' < V_z + dV_z$. The equation for f is:

$$\left(V_r \frac{\partial}{\partial r} + V_z \frac{\partial}{\partial z} + \frac{V_\varphi^2 - \theta^2}{r} \frac{\partial}{\partial V_r} - \frac{V_r V_\varphi}{r} \frac{\partial}{\partial V_\varphi} + K_z \frac{\partial}{\partial V_z} \right) f = 0$$

where: $K_z = -\frac{\partial \psi}{\partial z}, \frac{\theta^2}{r} = \frac{\partial \psi}{\partial r}$ ψ = gravitational potential.

In deriving the above equation, we have assumed $\frac{\partial}{\partial t} = \frac{\partial}{\partial \varphi} = 0$. ψ is to be determined from Poissons' equation which can be written:

$$\frac{-dK_z}{dz} = 4\pi G\rho - 2\frac{\theta}{r}\frac{\partial \theta}{\partial r}.$$

In order to obtain insight into the behavior of self-gravitating systems, a study of a simpler set of equations has been initiated which describes only the z-motion of stars; this simplification is obtained in the following way:

The form of the observed velocity distributions suggests that the z-energy is an integral of the motion.

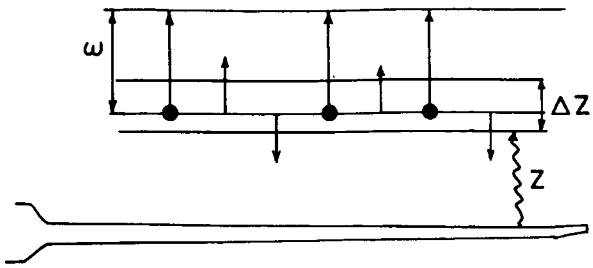
Further, in Poissons' equation:

$$\frac{-dK_z}{dz} = 4\pi G\rho - 2\frac{\theta}{r}\frac{\partial \theta}{\partial r}$$

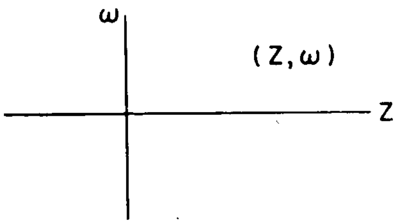
in the solar neighborhood, $\rho \cong 0.14 M_\odot / \rho_c^3$ whence $4\pi G\rho \cong 10^{-28}\ \mathrm{sec}^{-2}$. The second term on the right, in effect, measures the differential rotation. Expressed in terms of Oorts' constants, A and B, this term is $2(B^2 - A^2) = 10^{-30}\ \mathrm{sec}^{-2}$ or about 1% of the preceding term.

Neglecting this term will lead to the equidensity surfaces being parallel planes. This is observed to be the case up to a few hundred parsecs from the plane. This range is adequate since the density scale heights in the z-direction range from 50 parsecs for O,B stars to 350 parsecs for G, K and M dwarfs.

Thus, the model which may be abstracted from the three dimensional problem is the motion of plane parallel slab of stars in one dimension. For example, consider the following picture:



At some height z pick out all those stars with velocity ω. In phase space, since all of these stars have the same z and ω, they are represented by a single point.



And since they all have the same "initial conditions" they will continue to be represented by a point except for the effects of individual encounters between stars. But the relaxation time for binary encounters is of the order of 10^{12} years. So for times comparable to the age of the universe, "stars that initially phase together, stay together."

Our system can now be described by a one-dimensional Boltzmann equation and Poissons equation.

$$\frac{\partial f(z,\omega,t)}{\partial t} + \omega\frac{\partial f}{\partial z} + K\frac{\partial f}{\partial \omega} = 0$$

$$-\frac{dK_z}{dz} = 4\pi G\rho = \frac{d^2\psi}{dz^2}$$

$$\rho(z,t) = \int_{-\infty}^{+\infty} f(z,\omega,t)\,d\omega$$

This coupled system of equations possesses steady solutions of the form $f(\epsilon) = \frac{1}{2}\omega^2 + \psi$ where we have assumed unit mass slabs.

Solutions of the form $f \alpha e^{-\beta\epsilon}$ (isothermal) and $f \alpha (\epsilon - \epsilon_0)^n$ (polytropes) have been explicitly derived by Camm (MNRAS, 110, 305, 1950). Of particular interest is the isothermal solution, which is:

$$\rho(z) = \frac{M}{2l}\,\mathrm{sech}^2\,(z/l)$$

$$\theta(\omega) = (2\pi GMl)^{-\frac{1}{2}} e^{-\omega^2/2\pi GMl}\;;\; f = \rho\theta$$

$$l = 2\langle\omega^2\rangle / 2\pi GM$$

M = mass in unit column $\sim$ gm/cm^2.

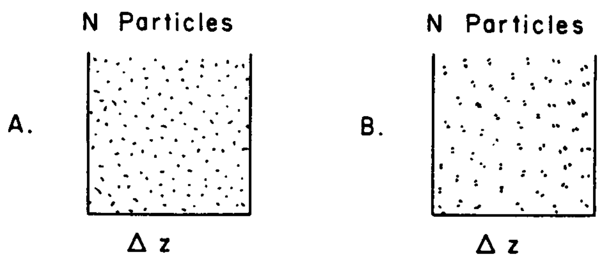
$$f(z,\omega) = \rho(t)\theta(\omega)$$

Note that because of the long range interactions, as the mass of the system (M) goes to ∞, the system shrinks to a point. This behavior holds if we increase the mass keeping the total energy constant (Microcanonical ensemble), or the energy particle constant (Canonical ensemble).

With a number of analytic solutions at hand, one might well wonder what else there is to be done. But it is this multiplicity of solutions that causes the difficulty. Compare this with the situation in statistical mechanics where one is led in time to one solution – the equilibrium solution. Instead, we have here a number of steady state solutions, and one would think that we would land in one of the other of them, depending on initial conditions. This, however, may not be the case.

In particular, the Boltzmann equation can be derived from the Liouville equation (a rigorously correct equation) via the BBKGY hierarchy.

The Liouville equation deals with the N-particle distribution function $f^{(n)} = f^{(n)}(z_1, \ldots, z_n, \omega_1, \ldots, \omega_n, t)$ which contains information on two particle correlations, three particle correlations, ... , up to N-particle correlations. By integrating out the phase coordinates of one particle after another, we can obtain an approximate equation for the two-particle distribution function $f^{(z)}(z_1, z_2, \omega_1, \omega_2, t)$. This can answer the question: given that there is a particle at z_1, what is the probability that there is another particle at z_2 ? To answer this same equation, the single particle (Boltzmann) distribution function must assume that these particles are uncorrelated. The single particle distribution function cannot distinguish between the following two cases:



But cases A ("atomic" stellar gas) and B ("molecular" stellar gas) behave differently; e.g., their relaxation times are different.

The equation for $f^{(2)}$ is

$$\frac{\partial f^{(2)}}{\partial t} + \omega_2 \frac{\partial f^{(2)}}{\partial z_1} + \omega_2 \frac{\partial f^{(2)}}{\partial z_2} + K_1 \frac{\partial f^{(2)}}{\partial \omega_1} + K_2 \frac{\partial f^{(2)}}{\partial \omega_2} = 0$$

this can be reduced (by integrating out the coordinates of particle 2) to an equation for $f^{(1)}$. If we write

$$f^{(2)}(z_1, z_2, \omega_1, \omega_2, t) = f^{(1)}(z_1, \omega_1, t) \cdot f^{(1)}(z_2, \omega_2, t) + g^{(2)}(z_1, z_2, \omega_1, \omega_2, t)$$

This equation is:

$$\frac{\partial f^{(1)}}{\partial t} + \omega \frac{\partial f^{(1)}}{\partial z} + K \frac{\partial f^{(1)}}{\partial \omega} = - \int dz'\, d\omega' K(z, z') \frac{\partial g}{\partial \omega} (z, z', \omega, \omega', t)$$

where K is again determined by Poissons' equation. Thus the term on the right hand side acts like a relaxation term, tending to destroy the steady state solutions of Camm.

One purpose of the present work is to estimate the size of this term.

This one-dimensional model is also convenient for statistical mechanics investigations, because the system is bounded in phase space, in contrast to the two or three dimensional case, where particles may escape, and where velocities may go infinite.

Thus it is possible, in principle, to do thermo-dynamics on this system and in fact, some attempts have recently been made (Salzberg, J. Math. Physics, 6, 158, 1965).

At present this problem is being studied both theoretically and experimentally. Experimentally, an IBM 7094 program numerically integrates the equations of motion for a finite number of slabs, considered as point masses with a force law independent of distance. The program is sufficiently accurate to integrate the equations of motion reversibly for astronomically long times (10^{10} years). Reversibility is crucial here, and to date 100 bodies have been integrated for 10^9 years; velocities have been reversed, and the 100 bodies evolved back to their initial configuration. Thus, relaxation by long range interactions can be investigated. Previous attempts to investigate relaxation times have been plagued by round-off errors which relaxed the system faster than the particle interactions. The results of the computation are plotted in phase space and continuously photographed. The photographs are processed into motion pictures which permits a view of the phase-space evolution, with the "time-sense" undistorted.

It is hoped that understanding of the present problem will lead to methods which can be applied to the more realistic three dimensional problems. In addition, however, this one-dimensional model is an accurate representation of the z-motions of stars in the solar neighborhood, and this is of immediate astronomical interest.

STELLAR POSITIONS AND MOTIONS

R. Stothers

Research was undertaken on the compilation of a catalogue of published data (over the last thirty years) on O and B stars. The object is a detailed discussion of the positions and motions of only the nearby stars, and, for this purpose, earlier catalogues have been found to be inadaquate. The compilation has been carried out mainly by a student assistant, Jay Frogel, who has continued the work this summer (1965) from where he left off last year.

INFRARED ASTRONOMY

Hong-Yee Chiu
(with W. Hoffman and N. Woolf)

Plans have been developed for a combined theoretical and observational program in infrared astronomy. Initial plans call for balloon flights with instruments, the critical element of the instruments being the use of an infrared detector cooled to liquid helium temperatures. There will be an all-sky scan with a resolution of 1.5 degrees. Eventually, satellite flights will be conducted.

THEORY OF TURBULENCE

Jackson Herring

I. DIAGONALIZING APPROXIMATIONS FOR THERMAL TURBULENCE

The direct interaction approximation has been applied to the study of isotropic turbulence by Kraichnan (1963). The numerical success of this theory, at moderate Rayleigh numbers, encourages one to consider its application to the thermal convection problem. The method of generalizing the direct interaction approximation to inhomogeneous problems has been indicated by Kraichnan (1964), and in principle its extension involves no new problems. In practice, however, the problems involved in such a generalization are rather severe. The main difficulties here are associated with the fact that one has, in a thermal convection problem, to use many more correlation functions to describe the statistical dynamics of the turbulence than in the isotropic problem. One must introduce equations for both the velocity and temperature auto correlation functions and velocity and temperature cross correlations. In addition to having to deal with more correlation coefficients, these qualities are no longer homogeneous (because of the preferred direction of gravity in the problem), but depend explicitly on the vertical coordinate. These complications make a direct attack on the thermal turbulence problem via the full direct interaction equations rather formidable, and it is therefore useful to search for simplified approaches in which the number of correlation coefficients necessary to make the computation is reduced by an order of magnitude.

The present research explores ways to abridge the full direct interaction equations by eliminating the necessity for computing certain of the cross correlations. Such a procedure (if valid) will reduce the turbulence problem to one of the same level as that involved in the isotropic turbulence problem. The sort of abridgment investigated here is to find a valid approximation in which the cross correlation coefficients are functions of the auto correlation coefficients. For example, suppose θ represents the temperature fluctuation field and T the horizontal average temperature field. Then both of these quantities may be expanded in an orthonormal set of functions whose amplitudes are θ_n and T_n, respectively. The expansion set is left arbitrary. Then to study the turbulence problem, one has to compute ensemble averages like $\langle \theta_n \theta_m \rangle$ which would be a cross correlation coefficient.

The type of approximation considered here involves writing

$$\langle \theta_n \theta_m \rangle = A_{nm} \langle \theta^2{}_n \rangle + A_{mn} \langle \theta^2{}_m \rangle$$

Here the coefficient, A, will, in general, involve T_n and will be derivable from a perturbation calculation which estimates the cross correlation coefficients. A method for doing this has been suggested by Kraichnan (1963) and essentially involves a method of treating off-diagonal couplings by a type of direct interaction argument.

In the calculation just sketched, the representation of the temperature field is left entirely arbitrary. There then arises a question of what is the best representation (set of functions) to use for the velocity and temperature fluctuation fields. For example, one could expand these quantities in a Fourier series or one could use the Laminar eigenmode functions. Or perhaps they could be represented more advantageously by some other set of functions. Presumably there exists an optimum representation in which the off-diagonal correlation coefficients are uniformly small. In the present research the diagonalized direct interaction approximations are carried out in several representations in order to find the optimum representation.

The numerical results were performed for the following three representations:

1. Fourier mode,
2. Laminar eigenmode,
3. "Modified Laminar eigenmode."

The numerical computations were limited to the infinite Prandtl number case in order to simplify the analysis which would otherwise be prohibitive. A brief resume of the results follows.

1. Fourier Mode Representation

The diagonalized direct interaction approximation was first carried out for Fourier mode representation. The results indicate that the off-diagonal correlation coefficients became large (although not unreasonably large) in the sense of violating Schwartz's inequality. The calculations were extended to very large Rayleigh numbers so that the curve of Nussult number versus Rayleigh number could be constructed. It was found that the Nussult number depended on the fifth root of the Rayleigh number and that, therefore, this representation is not a realistic one. Also in this representation the correlation coefficients are large (around 30%); this indicates a breakdown of the perturbation treatment of the off-diagonal terms.

2. Laminar Eigenmode Calculation

a. Non-conservative

By using the Laminar eigenmode expansion one is able to write the thermal convection equations in a diagonal form (Spiegel, 1963). That is to say, only the nonlinear fluctuating self-interactions appear in this form of the equations: the fluctuating mean field interactions occur diagonally as linear decay or growth term rates. It has been suggested that in this representation the off-diagonal correlation coefficients can be completely neglected. A priori, this appears to be entirely plausible. The diagonalized approximation was therefore carried out for this representation. The numerical results were not physically consistent. The most important aspect of the non-physical behavior is the violation of the conservation of energy. It therefore appears that the off-diagonal correlations were important in maintaining energy conservation and cannot be entirely negligible.

b. Conservative Form

The next approach to the problem was to introduce the Laminar eigenmodes into the equations of motion in the conservative fashion. That is to say, the equations of motion were not subjected to that transformation which eliminated the off-diagonal pair correlations. In this form the conservation properties were preserved. The off-diagonal terms could then be computed by using an extended form of the diagonalized direct interaction approximation as proposed by Kraichnan. The form proposed by Kraichnan had to be extended because of the presence of time derivatives as coupling coefficients among the mode amplitudes. The numerical calculations performed for this case gave satisfactory results. The correlation coefficients were of the order of 2-3% (at their maximum). The Nussult number was proportional to the cube root of the Rayleigh number as it should be.

3. "Modified Laminar Eigenmode"

The results of section 2 (b) were generalized by modifying the expansion set so as to make equal to zero the off-diagonal pair correlation coefficients (as evaluated by the diagonalized approximation). From the point of view of perturbation theory, this appears to be the best possible choice of representation. The results of this calculation were very similar to 2 (b), except, of course, that the correlation coefficients were zero. The difference between the calculations in 3 and 2 (b) varied by 5-10% and showed some significant differences in the mean temperature profiles.

The calculations are presently being generalized to permit a more realistic numerical approach to the problem.

II. SELF-CONSISTENT FIELD APPROACH TO TURBULENCE THEORY

A self-consistent field type perturbation theory is developed for treating the dynamics of stationary and homogeneous turbulence. The method is a modified perturbation technique for computing the probability distribution function for the turbulent velocity. It consists of expanding the probability distribution function about the product of exact univariant distributions of all the Fourier models. The method is very similar to the Hartree self-consistent field method in principle.

The theory is used in second order to find expressions for the turbulent energy spectrum and associated response frequencies. The results closely resemble the direct interaction approximation results and are related to the random phase approximation of Edwards. The theory is compared in detail to that of Edwards.

From this research a paper has been submitted to the Physics of Fluids. The method has also been extended to the case of non-stationary turbulence.

ASTROPHYSICAL HYDRODYNAMICS

A. J. Skalafuris

The general long-range program of fundamental research described below is an imperative forerunner to the correct solution of astrophysical problems. The purpose of this fundamental research is to clarify the gross problems of astrophysical hydrodynamical flow in terms of microscopic atomic phenomena, and to express these relations in terms other than those obtained from dimensional analysis, the literature of engineering and phenomenological argument.

A. PROPAGATION, GENERATION AND ORIGIN OF PROGRESSIVE WAVES:

With the advent of computing machines, many research problems in hydrodynamics have been linearized over small regions and a conjunction of many such small regions has been iterated in lengthy procedures by the electronic machines. However, understanding of the phenomena must extend beyond numerical work and necessitates analytic work with the non-linear equations. The analysis and behavior of non-linear differential equations as an investigation distinct from their formal solution yields much information useful to understanding the behavior of atmospheric phenomena reproduced by computing machines.

The equation of motion of a wave encountering density, gravity and pressure variations of an atmosphere is known in terms of parameters representing dissipation and radiative emission. Thus, the problem of propagation is directly coupled to the problem of shock structure. An interesting feature of wave motion is its ability to cool as well as heat. General arguments applied to a stellar atmosphere show that heating or cooling depends upon the ratio of escape velocity to acoustic velocity. Fluctuations in atmospheric thermal content occur in those atmospheres that have fluctuations of this ratio about unity. The sun between the photosphere and the chromosphere, the earth between the equator and its poles, and variable stars between expansion and contraction all show this fluctuation; hence, definitive alternating heating and cooling effects should occur in these stars.

Contrary to general opinion, waves are not necessarily accelerated down a density gradient in the presence of gravity, radiation pressure and an inertial reaction to the dynamics of an atmosphere. A wave may decelerate, converting its energy of motion to internal energy of the gas surrounding it. This effect is a function of the atmospheric properties, independent of boundary conditions. Thus, a gross classification of waves as either sub- or supersonic, expanding or imploding, will also designate regions in an atmosphere according to physical properties where heating or cooling occurs by wave motions. The problem of generation of high energy is reduced to a discovery of conditions under which the thermal content of a gas will be converted into energy of wave packet; thus, the origin of progressive waves is a region of aerodynamic cooling. The reflection of a progressive wave occurs in transition from one zone to another when it passes from accelerated to decelerated motion. The distance a wave will travel before reflected depends on its boundary conditions, i.e., the energy in the packet.

This represents the basic physical content of the phenomena of dissipation, propagation and reflection. Detailed analysis still requires the use of a computer; however, an analysis of the non-linear equations permits a selection of important characteristics for more delicate consideration. Bernard Goldstein has been programming a number of problems in order to accumulate a set of curves that will give general properties of waves in stellar atmospheres. The radius of curvature of a wave over the scale height of the medium characterizes a stellar atmosphere (R/H), and the strength of the wave vs. its displacement can be plotted for various values of (R/H). In stars, this ratio is not constant; hence, an application to a definitive stellar model may be close at hand once all the results under ideal conditions are fully understood.

B. STABILITY:

Dissipative and deformative stability of a wave front are responsible for the birth and death of a wave. A wave heats a medium by giving up its motion to the internal energy of the fluid. The moving wave packet can be viewed as an engine in contact with the infinite heat reservoirs in front and back. Following a particle through the wave packet traces out a heat cycle that forms a closed loop in the temperature-entropy plane. The area of this loop is the dissipation. If the process goes counterclockwise, the dissipation is positive and the medium is being heated; if clockwise, the medium is being cooled. The ratio of the area of the cyclic loop to the area under the hottest process of the cycle represents the fractional amount of dissipation in the propagating heat engine. For shock waves in monoatomic gases, this fractional dissipation rises to a maximum of 40% at low mach number ($\sim$1.3), then descends to 20% in the limit of infinite mach number. Each particle that penetrates the wave receives only about 80% of the energy in the wave front. The complete depletion of the wave front is only a matter of mass penetration. If the cycle is reversed, then a particle is cooled in crossing through the wave by the rarefactive effect produced behind it, and the dissipation is negative. Intermediate to these regions of positive and negative dissipation is a region of zero dissipation, and hence zones of stability, marginal stability and instability exist for the dissipation cycle.

Deformative instability is the cause of a turbulent spectrum. A coherent wave front cannot exist because the cross symmetries of the fields it encounters tend to drive it into many different modes. The stability is then a function of the symmetry of fields in the fluid. In a star these are radial and it is found in general that the only deformative modes that can exist are those whose momentum vectors point radially outwards. Thus, in a turbulent spectrum of gas motions, those wavelets that are oriented outward will be stable and can form progressive waves. There is also a selection of certain energies that coincide with the field intensities. The growth rates of instability are minimized at points in the spectrum, in resonance with the local physical parameters of the fluid. Hence, at various depths of a star, wavelets oriented outward of particular energy will be filtered out as progressive waves. The deformative stability, then, is a function of the geometric symmetry of the fluid and its field intensity. The deformative stability depends upon the microscopic reactions possible in the wave, i.e., ionization, radiative recombination. Computations are now in progress, whose purpose is to show that the absence of turbulent broadened shock heated lines in certain cepheid stars is due to the deformative stability of the wave. W. Virginis is such a star that has been observed with sufficient accuracy and regularity to allow a comparison of theory and experiment.

C. STRUCTURE:

The calculation of the profile of a shock wave throughout its relaxation requires the use of a theory of coupled transport and radiative transfer. All attempts to employ radiative diffusion have failed because photon mean free paths through a shock wave are much longer than the temperature gradients. The fact must be faced that non-thermodynamic equilibrium radiative processes cannot be ignored without destroying the phenomena under study. It is hoped that within the next year, a machine program will have been constructed that gives the entire non-equilibrium structure of the shock wave, including atomic populations and the non-Plankian continuum radiative emission spectrum. This problem is immense in magnitude and has occupied one numerical analyst, Dr. J. Conn, over the past half year. Results are promising, and we hope before the year is terminated, preliminary results of these programs will be evident.

This program involves some fundamental studies in non-LTE collision processes. Among them is the form of the electronic distribution function that deviates from normal in the shock wave. Mr. Milton Pine has been assisting in the analytic details of obtaining a solution to the problem of an ionizing gas through the use of the Lorentz approximation of transport theory. A solution in analytic form is necessary in order to accomodate the variety of conditions possible in an atmosphere.

Mr. David Linsker has been developing equations that will give parameters for the compressibility of propagating waves from the microscopic equations. He has also undertaken investigations to extend the propagating equations to special relativity. This latter effort is in its most preliminary stage since published material is sparse on this subject. Because a host of classical expressions has thus far been derived, an advantage exists in investigating relativistic effects because they can be verified by a consistency check with our classical expressions now developed and at our disposal. This investigation is being eagerly pursued for these reasons, and represents one of the more fundamental studies undertaken.

The field of inelastic collisions at low energy has been ignored because many of the methods of quantum mechanics are valid only in the high energy limit, i.e., Born approximation. With the attraction of high energy phenomena to physicists, little attention has been given to these cross sections and hence, long, involved and questionable techniques of extracting these quantities from observations are employed by astronomers. Several advantages exist in the calculation of these rates. They generally occur in cold gas, i.e., temperatures far below the ionization temperature;

hence, most atoms are in the ground state. The low speed of colliding particles polarizes the bound electrons along the direction of collision so that they follow the colliding particle around its secular orbit; thus, all forces are central and no interaction occurs because the angular phase of the colliding and target particles differ. Even though preliminary investigations led to sketching out a solution, this problem has not been pursued in great detail for want of a competent graduate student who has interest in it.

D. THE ANALYSIS OF OBSERVATIONS:

The wealth of data inherent in the spectra of pulsating stars has fascinated observers, and an enormity of data has been recorded. Most of it has gone without synthesis of its finer structure because the importance of cepheid stars in fixing distance scales has overshadowed interests in other aspects of the structure of these stars. Shock waves heat the atmosphere of the star and create a heat bath in which a sprinkling of the rarer elements emit a spectrum that changes with the periodic phase changes of the star. This spectrum does not match any of the standard spectral classifications of stars. Thus, some of the rare metallic abundances are provoked into emission by the shock wave, and if its progress could be followed in its journey, the radial distribution of these elements would be available. The emission lines of shock-heated lines display thin absorption cores displaced somewhat redward, interpreted as the pre-shock ionization of cold gas by the hot post-shock emission. The relative displacement of these cores gives the pre- and post-shock temperature ratio, hence, the shock strength. From this parameter, the shock structure should be inferable, hence, its emission spectrum.

This summer, Joel Schwartz has undertaken a project of removing the hump from the ascending branch of the luminosity curve of R. R. Lyrae. This hump is attributed to the ultraviolet radiation by the shock wave that appears during that portion of the cycle. Preliminary calculations show all orders of magnitude are correct and self-consistent with this assumption, and the detailed examination of data is justifiable. The most difficult problem is the removal of the quantum noise from the ultraviolet spectrum of the star. A theory of photon diffusion for the spectrograph and plate is being developed and it is hoped that it will resolve the noise problem. This noise, it should be pointed out, cannot be removed by a root-mean-square process as has been used extensively up to now.

A photon may be scattered in any direction; hence, any spectral interval may receive contributions from any other spectral interval. This is a diffusion process that integrates over the entire spectral range of the plate. A method to remove this integrating process necessitates the solution for the integrand given the integrated result. The integrand is a product of the diffusion kernal and the original spectrum.

Because integral equations ambiguously contain many extraneous solutions, such a process requires a strong presupposed knowledge of the physical result in order to abstract it from this process. Difficulties arise with those stars whose entire pulsational period cannot be viewed during one evening, and for which drastic terrestrial atmospheric changes occur before the next cycle can be duplicated. In this case the error is not a diffusion process affecting the entire spectral range, but a translation in phase of that part of the curve viewed during one sitting, and depends on the average meteorological opacity during the particular night of viewing. How to obtain this information is a question without an answer at the moment, but a question fundamental to astrophysics, since the court of judgment of any theory lies in observation, and as theories become refined, so must the interpretation of data. Because both observation and recent theory agree on the dynamic state of a stellar atmosphere, these problems in wave motion with non-LTE (local thermocynamic equilibrium) radiative transfer through fluids with collisional dis-equilibrated atomic populations are a first step towards understanding the gross external stellar structure.

STAR FORMATION PROBLEMS

A. G. W. Cameron

The problems of star formation were considered at some length in the paper "The Formation of the Sun and Planets," Icarus, 1, 13, 1962. In this paper the various terms entering into the virial theorem expression for gravitational instability of the gas cloud were considered in relation to the probable values of physical quantities present in interstellar space. It was concluded that the optimum conditions for formation of a cluster of stars consisted in the prior formation of an interstellar gas cloud with a density of about 10^3 hydrogen atoms per cubic centimeter and with a total mass of the order of 10^3 solar masses. Such a cloud could be produced by ionization effects of O and B stars in the interstellar medium, which would cause pressure imbalances, thus pushing neutral material along the magnetic lines of force until a dense cloud had been achieved. With these initial conditions, gravitational forces can overcome thermal and other expansion forces, and the magnetic field content of the gas cloud will not be an impediment to fragmentation until masses of the order of a solar mass have been obtained.

In the resulting collapse of the gas cloud, it was considered that a typical fragment would undergo several stages of contraction and collapse. It was supposed that the collapse would first be halted when the protostar was of a rather large size, so that the interior would become rather opaque and the radiation released by the collapse would not be able to escape freely. However, Gaustad showed that the opacity would not be sufficiently high to halt this initial stage of collapse. Consequently, the collapse goes directly into the next stage, the dissociation of hydrogen molecules. This sets in when the hydrogen in the interior of the protostar is heated beyond 1800 °K. The energy for the photo-dissociation of the hydrogen molecules must come from released gravitational potential energy, and this requires that the collapse continue until the protostar has a radius of only a few astronomical units. However, similar considerations then show that the hydrogen in the interior of the protostars becomes partially inonized, and an additional release of gravitational potential energy is needed to ionize the hydrogen and also the helium. Consequently, the collapse must continue until the protostar of solar mass has reached only 1/3 of an astronomical unit in radius. This assumes, of course, that rotational flattening would not occur.

It was apparent, however, that the collapse would not be able to occur to such a great extent without rotational flattening of the protostar. A reasonable and conservative estimate for the angular momentum likely to be contained by the protostar would correspond to the original interstellar cloud rotating once per revolution of the gas around the center of the galaxy. With the collapse history outlined above, it was then shown in a paper entitled "Formation of the Solar Nebula" published in Icarus, 1, 339, 1963, that a rotational flattening of the fragment would produce a disc having a radius of many tens of astronomical units. Furthermore, this disc would have a density distribution within its interior such that there would be no central star formed in the middle. Consequently, the subsequent evolution of the gas to form in general a star, or in particular the sun, would require a mechanism of dissipation of this primitive solar nebula.

It was originally suggested that the conversion of rotational shear energy into enhanced magnetic field energy would be sufficient to do the trick. However, more recently it has appeared that turbulent processes within the nebula are likely to be far more effective in dissipating it. The role of turbulence in cosmic gas masses was first discussed at some length by von Weizsacker. Using von Weizsacker's ideas, ter Haar showed that the turbulent dissipation of the gaseous disc should occur in a time scale of the order of a century. However, as was later shown by Parker and Safronov, the ordinary ideas of turbulence cannot be directly applied to a disc of this sort, since the angular momentum per unit mass increases outwards. This gives rise to restoring forces which tend to restore any element of the nebular displaced radially toward its original radial position. It is evident, therefore, that turbulence must be a much smaller scale phenomenon, where the turbulent forces are able only to overcome the small scale restoring forces when the displacements are not too great. Consequently, the dissipation of the solar nebula is likely to take much longer than a century, but nevertheless it may not be unreasonable to assign this time scale as something of the order of 10^6 years.

The principal effect of dissipation of the primitive solar nebula is to lead to the inward flow of most of the mass, but with an outward flow of some mass in the exterior regions of the nebula in order to conserve angular momentum. After the inward flow of gas has formed the sun, as will be indicated below, the intense convection zone of the sun is likely to generate a strong solar wind. It is presumably this solar wind which is responsible for the dissipation of the outermost parts of the solar nebula. Quite large amounts of solid materials should be left in the outer parts of the solar system, presumably in the form of comets, and Whipple has recently discussed some of the evidence regarding the possible existence of this cometary material.

XENON COMPOSITION PROBLEMS

A. G. W. Cameron

Many detailed investigations during the last few years have shown that the composition of Xe in the meteorites differs from that in the earth's atmosphere. The variations are of several kinds. The meteorites frequently have excesses of mass number 129, which is to be attributed to the decay of the extinct radioactivity I^{129}. This has a half life of 16 million years. The atmosphere shows an excess of isotopes which can be formed as a result of the decay of fission fragments. This process is usually attributed to the decay of an extinct radioactivity Pu^{244}, with a half life of 76 million years. In addition, the lighter isotopes of xenon show variations which cannot be due to either of the two previous causes. These variations have been attributed to the results of neutron capture in the sun, during the deuterium burning stage of early solar evolution, with the subsequent capture into the atmosphere from the solar wind of the altered xenon. These problems have been discussed in the paper entitled "The Formation of the Sun and Planets," Icarus, 1, 13, 1962; "Origin of Atmospheric Xenon," Icarus, 1, 314, 1963; and "Interpretation of Xenon Measurements," a chapter in The Origin and Evolution of Atmospheres and Oceans, (New York, 1964) edited by P. J. Brancazio and A. G. W. Cameron.

The current outlook on these problems is as follows. The I^{129} present in the meteorite parent bodies which has given rise to excesses of Xe^{129} has very probably been produced by charged particle bombardment in the primitive solar nebula. There is some evidence to suggest that this bombardment occurred while the material was in fairly finely divided chondrule form in the nebula. Such particle acceleration probably accompanies flares produced by the interaction between the turbulence which dissipates the nebula and the magnetic field embedded in the nebula. It also seems very likely that the liquid phase of the basic chondrules is produced by the gas compression and heating which takes place in these flares owing to the annihilation of magnetic field energy. The Pu^{244} giving rise to much of the xenon in the earth's atmosphere appears to come from the Pu^{244} produced as a result of galactic nucleosynthesis; it would be present in the primitive solar material when the solar system was formed. The fact that the earth's atmosphere does not contain a large spike at Xe^{129} implies that the material going to form the earth was irradiated to a much less extent than the material forming the meteorites.

The changes in abundance among the lighter xenon isotopes, attributed to neutron capture as a result of deuterium thermonuclear reactions in the sun, can be accounted for quantitatively within the uncertainties of the nuclear parameters involved. It is at present planned to incorporate these calculations specifically into some calculations of solar evolution during its deuterium burning phase, in order to make an evaluation of the effects of a variation in temperature on the process of the deuterium burning. The details of the process by means of which the xenon is captured into the atmosphere are not known, but it is apparent that the extraction of the xenon ions from the solar wind must be a fairly efficient process. It could be that the much larger Larmor radii of the xenon atoms, associated with the incomplete stripping of the electrons from the xenon atoms in the solar corona, may be responsible for this capture of the xenon despite the fact that solar wind particles in general are not captured.

GEOMAGNETIC ACTIVITY

A. G. W. Cameron

In collaboration with Dr. H. L. Stolov, the relationship between variations in the geomagnetic Kp index with the phases of the moon has been investigated. A small but apparently statistically significant variation has been found, consisting of a depression of the index for nearly a week prior to full moon, and the enhancement of the index for a week afterwards. It was originally thought that this might denote some interaction between the moon and the geomagnetic activity being propagated as hydromagnetic waves up the magnetospheric tail. However, a subsequent suggestion of C. O. Hines has indicated that it is probably more profitable to look for an explanation of this effect in the interaction between solar and lunar tides in the ionosphere. Solar and lunar effects are normally removed from the Kp index, but the interaction between the tides may not have been removed, and this may possibly account for the effects that are observed. These results have been published in a paper entitled "Variations of Geomagnetic Activity with Lunar Phase," by Harold L. Stolov and A. G. W. Cameron, Journal of Geophysical Research, 69, 4975, 1964.

It is also interesting to consider whether there may be some correlations between geomagnetic activity, lunar phase and the red luminescence sometimes observed on the lunar surface. It has been shown at Manchester that particle bombardment of any kind on the material of enstatite achondrite meteorites gives rise to such a red glow. Enstatite achondrites are meteorites of essentially stony composition from which free iron has been removed, presumably by heating. This composition is essentially that which an earth rotational instability model of lunar origin would suggest for much of the moon's surface. Since continued bombardment probably reduces the fluorescent efficiency, it should not be surprising that the effects are found near the newer craters where freshly exposed material would be present. The basic problem is to account for the fairly intense particle bombardment which must be present. Initially, in a paper entitled "Particle Acceleration in Cislunar Space," by A. G. W. Cameron, Nature, 190, 785, 1964, it was suggested that the bombardment might come either from particles in the magnetospheric tail or by particles accelerated by turbulent magnetic fields in the region between the magnetospheric boundary and the bow shock which stands off from the magnetosphere in the solar wind. Subsequently, the measurements at Manchester have suggested that bombardment efficiencies are less than previously indicated, and, consequently, it appears now that the suggestion about particle bombardment from the magnetospheric tail is the most likely explanation of the luminescence.

NATURE OF THE LUNAR SURFACE

A. G. W. Cameron

It has been known for a long time that the photometric properties of the moon are very unusual. Recently, Hapke and Gold at Cornell have shown that these photometric properties can be understood if the lunar surface is composed of very underdense material. They have reproduced these photometric properties by preparing surfaces by shaking small grains of powder through a sieve so that they fall individually and stick to one another upon contact, the van der Waals forces being greater than the gravitational forces. If the powder is also a dark powder, so that multiple scattering is eliminated, then the light is strongly scattered back in the direction of incidence since that is the direction in which the least shadow will be seen.

The problem of the degree of underdenseness which will be produced when particles fall individually, but at random, and halt upon contact with other particles has been investigated. For this purpose various regular geometric shapes have been figuratively dropped in a computer to find where they will stick. A variety of cases have been run. Spheres of the same radius have been dropped vertically, and other spheres of the same radius have been allowed to impact with an isotropic distribution of directions. Also, spheres of a variety of radii have been dropped vertically and spheroids have been dropped vertically. There are some differences between the bulk density of the material which is built up from these objects, but in general it can be said that the density is less than the density of the spheres by a factor 7 to 10. This agrees well with the observations made experimentally by Hapke and Gold at Cornell. Thus, it confirms that their analysis of the sticking probability of the particles is essentially correct. It has also been important to find that the isotropic incidence case gives results not directly different from that for the vertical incidence case. These results may also be interesting in the case of the structure of cometary material, where a similar accumulative mechanism may be involved.

THE ANGULAR DISTRIBUTION OF SCATTERED SOLAR RADIATION AND THE EARTH ALBEDO AS OBSERVED FROM TIROS

Albert Arking

The TIROS satellites provide us with a unique opportunity to view the planet Earth from the same detached point of view applied to other planets in the solar system. A study of the solar radiation scattered from the earth's aerosol and underlying surface should enable us to check theoretical models of planetary atmospheres, in general, and learn about the molecular and aerosol properties of the earth, in particular. In addition, almost as a by-product, we obtain the earth's albedo, a critical quantity in the earth's energy balance.

For the present study, data based upon TIROS IV radiation measurements in one spectral interval (0.2 to 6 microns from Feb. 8 to June 30, 1962) were utilized to determine the angular distribution of scattered solar radiation and to use this observed distribution to compute properly the earth's albedo.

During that period of time there were approximately 5 million measurements taken over the quasi-globe (that is, the region of satellite coverage from 60° South to 60° North latitude) at various angular positions of the satellite and at various solar zenith angles.

Ideally, what we would like to have is the mean intensity of scattered radiation as a function of latitude, longitude, solar zenith angle, the two angles of the outgoing direction and the time period. This involves 6 independent parameters. However, the 5 million measurements are too few to meaningfully separate them into a 6-dimensional array. The data, therefore, was analyzed as follows:

First, the data was separated with respect to the three angles (two angles representing the direction of reflected ray and the solar zenith angle) but without regard to geographic location and month. We call this data "the angular distribution."

Second, the angular distributions from several restricted geographic regions were compared and found to be quite similar. Comparison of the angular distributions from each of several of the months also showed striking similarities. A further comparison was made between extensive cloud coverage and sparse cloud coverage and only slight differences were found in the angular distribution. We concluded that the angular distribution does not depend very strongly on cloudiness, geographic location or month.

I would like to caution that this conclusion applies only to data averaged over some suitable period of time (in this case, one month). It would not necessarily apply when comparing one cloud configuration with another or when comparing the data at one location at one instant of time with data at another location or another instant of time.

Third, having obtained a universal angular distribution function, we proceeded to establish a table of conversion factors, based upon this angular distribution function. This enabled us to convert each radiation measurement into an albedo value, taking into account for each measurement the direction of the satellite and the sun.

The albedo values were then separated according to geographic location and month. From the mean albedo in 5-degree latitude-longitude intervals, the latitudinal distribution of albedo was obtained.

To illustrate the procedures outlined above:

<u>Figure 1 defines the terms and symbols:</u>

ζ (zeta) is the solar zenith angle.

θ (theta) is the satellite zenith angle.

Ψ (psi) is the relative azimuth angle between the sun-zenith plane and the satellite-zenith plane.

I denotes the emergent intensity, which is a function of the three angles.

R called the "apparent reflectance," is the ratio of the measured intensity to that of a perfectly, diffuse reflector. R would be the true reflectance if the surface were diffuse.

$\bar{R}$ the true reflectance, is obtained by averaging R over the outgoing hemisphere weighted by the cosine of the zenith angle.

A the local albedo, is obtained by averaging $\bar{R}$ over the range of possible solar zenith angles weighted by the solar radiation function, W, which depends upon solar zenith, latitude and solar declination.

Figure 2 shows the grid used in separating the data with respect to angular distribution. There is one such grid for each of 20 intervals of the solar zenith. On this grid, θ is along the radius and Ψ is around the polar axis.

Measurements from the radiometer were distributed among the 223 sections and a mean value of R was obtained in each section.

To examine the dependence of the angular distribution upon cloudiness, we applied the crude technique of separating the measurements in each section into 2 groups:

(1) high-level values, which were values of R above the mean for that section; and

(2) low-level values, which were values of R below the mean for the section.

The high-level values were assumed to correspond to extensive cloudiness and the low-level values to sparse cloudiness.

In the following figures the combined data is labeled "Mean," the high-level data "Above Mean" and the low-level data "Below Mean."

In figure 3 the mean values of R are plotted as a function of Ψ for two satellite zenith angles and several values of the solar zenith. In the upper portion of the figure, θ is between 55° and 62° and the four curves correspond to four values of μ (cosine of the solar zenith angle). We find the anisotropy is more pronounced the lower the value of μ. In other words, as the sun approaches the horizon, the intensity becomes more anisotropic. In the lower portion of the figure θ is between 62° and 71° and the four curves correspond to the same four intervals of the solar zenith. The anisotropy is more pronounced for the larger values of satellite zenith angle. As expected, when the sun is directly overhead (μ between .95 and 1), the intensity is independent of azimuth.

The curves in Figure 4 are obtained by averaging R over the azimuth angle Ψ and plotting it as a function of θ, the satellite zenith, for four different solar zenith intervals. One notes from this and the previous figure that as μ approaches 1, the intensity becomes isotropic; it becomes increasingly more anisotropic as μ approaches 0.

It is interesting to compare our measurements with the results of theoretical calculations. In Figure 5, the observed values of R, indicated by the heavy, solid lines, are plotted in the plane containing the sun and zenith. The abscissa is the satellite zenith angle, the left side for $\Psi = 180°$ (when the satellite is looking from the side opposite to the sun), and the right side for $\Psi = 0°$ (when the satellite and sun are in the same direction). The plotted values correspond to a "clear" atmosphere (the "below mean" data described above). In order to eliminate the influence of the reflectivity of the underlying surface, the data for this curve have been selected from a region in the Pacific Ocean, which has a reflectivity of less than 5 percent. The TIROS values are compared with the calculations of Coulson, Dave and Sekera (1960), indicated by the broken line, for a Rayleigh atmosphere with zero surface albedo. We note that the theoretical curve is symmetric, whereas the observed curve has a very strong forward peak.

The theoretical curves are shown for two values of the optical thickness 0.10 and 0.25. The actual optical thickness of the molecular atmosphere varies with the wavelength, λ, faster than $1/\lambda^4$. The optical thickness of 0.10 corresponds to λ = 5500 Å and 0.25 corresponds to λ = 4400 Å.

The large discrepancy between the Rayleigh and observed distributions could be due to either of two effects, or a combination thereof:

(1) neglecting the specular reflection component in the theoretical calculations;

(2) the effect of dust and water droplets.

In the upper portion of figure 5, for $\zeta = 78.5°$, one cannot distinguish between the contributions of a specular reflection component and the contributions of scattering particles very strongly peaked in the forward direction (as in the case for dust and water droplets). In the lower portion of the figure, for $\zeta = 53°$, the specular direction is shifted toward the center and a strong forward peak is still apparent in the distribution.

Calculations using phase functions with considerable forward-backward asymmetry have been made by Feigelson et al (1958) and two resulting distributions are compared with the TIROS data in Figure 6. The phase functions used were the most extremely asymmetric of the ones considered by Dr. Feigelson. One curve is for an optical thickness of $\tau = 0.6$ and the other for $\tau = 0.2$. It seems that these phase functions are not peaked forward enough to match the TIROS data.

In making comparisons with theoretical models, it must be emphasized that we have not completely eliminated cloud contamination and the measurements are integrals over the entire spectrum from 0.2 to 6 microns.

Cloudy data is compared with non-cloudy data in Figure 7, by plotting the mean, above mean and below mean values of R divided by $\overline{R}$ in the sunzenith plane. Although the differences are small, there is an indication that the non-cloudy data (below mean) is more anisotropic. It is interesting to note that the cloudy data (above mean) has a backward peak equal to the forward peak, consistent with the theory for a

Rayleigh atmosphere overlying an isotropic surface. That the differences between cloudy and non-cloudy data are small is further indicated in Figure 8, where R divided by $\bar{R}$ is plotted as a function of the azimuth angle for fixed satellite and solar zeniths.

A further illustration is shown in Figure 9, where we plot R (averaged over azimuth) divided by $\bar{R}$ as a function of θ. Again, there is a small but noticeable indication that the non-cloudy data shows greater anisotropy.

Figure 10 is a plot of the true reflectance, $\bar{R}$, versus the solar zenith. $\bar{R}$ is normalized so that the mean, below mean and above mean could be compared. We note that the non-cloudy data shows a slightly greater dependence upon solar zenith.

The fact that the difference in angular distribution between cloudy and non-cloudy situations is small, agrees with the results of theoretical models calculated by Mrs. Feigelson and her collaborators.

We have also found that the angular distribution does not depend very strongly on geographic location. An illustration is shown in Figure 11 where R divided by $\bar{R}$ is plotted in zenith-sun plane for 3 different geographic regions and for the entire quasi-global region. The 3 geographic regions are the Pacific Ocean, tropical latitudes and mid-latitudes. The differences are seen to be small.

We have also compared the angular distribution for different months and again found very small differences. Therefore, the quasi-global mean angular distribution was adopted to give the correction factors needed to convert each intensity measurement into a value for the albedo.

The resulting albedo values were distributed into 5-degree by 5-degree latitude-longitude squares for each month. From this we averaged over longitude to obtain a latitudinal distribution of albedo.

The latitudinal distribution of albedo is shown for the month of February in Figure 12. The solid histogram shows the albedo values corrected for the anisotropic angular distribution. The uncorrected values (obtained by assuming diffuse reflection) are shown by the dashed histogram. Note that there are differences as much as 20% in the albedo at some latitudes.

The small circles indicate the albedo that would be obtained if the values were not corrected, but the data were selected so that the satellite nadir angle was a maximum of 45° (corresponding to a maximum zenith angle of 53°) and the solar zenith angle restricted to 70°. These correspond to the values Mr. Bandeen has used in the previous paper. It is seen that cutting off the high values of ζ and θ lead to substantially improved results in this case, close to the corrected values.

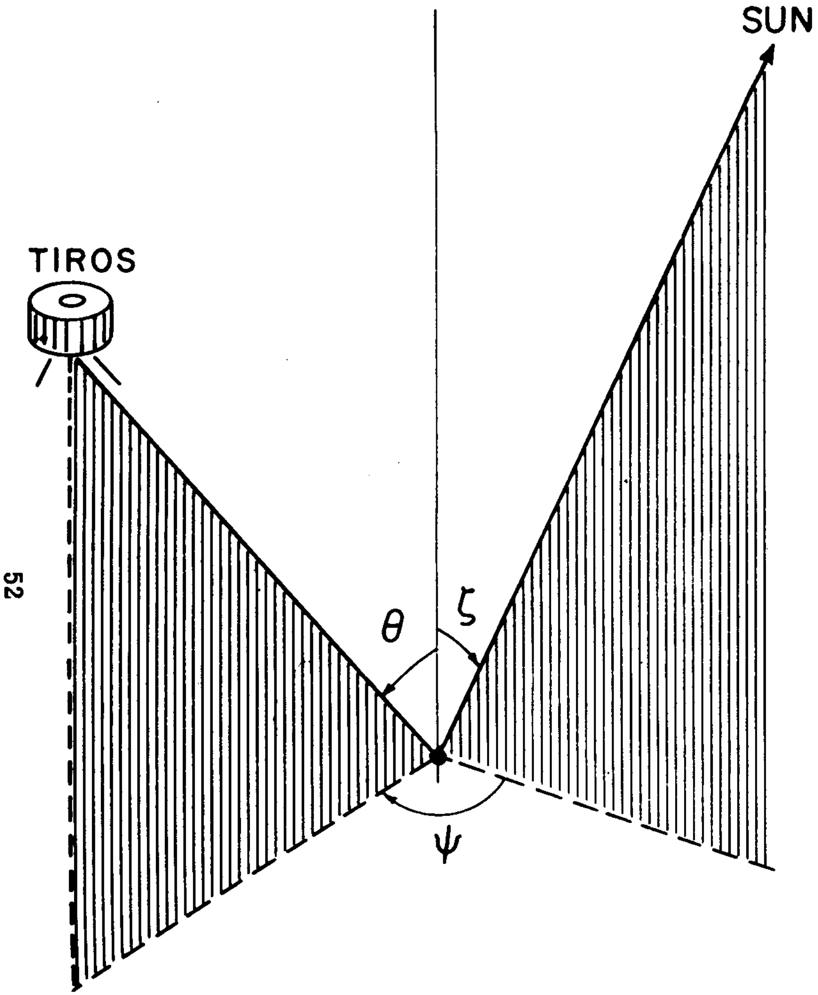
That the cut-off procedure does not always improve the results can be seen in the data for June, shown in Figure 13. Here we see a substantial difference between the albedo values corrected for anisotropy and those values obtained by the cut-off procedure.

The latitudinal distribution of albedo for the months February through June, 1962, corrected for angular anisotropy, is shown in Figure 14. I would like to call attention to the local maximum that is slightly south of the equator in February and moves northward in successive months up to June.

It is interesting to compare the albedo with the cloud cover distribution obtained from an analysis of the pictures transmitted by the same satellite, TIROS IV. The lower curve of Figure 15 shows the albedo versus latitude for the period February 8 to June 30, 1962 in the manner described earlier. The upper curve shows the percentage cloud cover versus latitude obtained from approximately 5000 TV pictures from TIROS IV cameras, analyzed by computer. The method for analyzing the TIROS pictures was reported last year at the COSPAR meeting and 6 months ago in an article in Science. Note that the position of the local maximum in the tropics is the same in both curves and the two curves follow each other quite well except at latitudes beyond 45° or 50°. This difference warrants further investigation to establish whether this is real or spurious.

Figure 16 shows a table which gives the albedo for the months February through June as well as for the mean during that period. The first column gives the quasi-global albedo (that is, the albedo for the region 60° south to 60° north latitude). To obtain the global albedo, it is necessary to make assumptions about the albedo in the polar regions. The second column gives the global albedo for an assumed polar albedo of 50 percent and the third column for an assumed polar albedo of 50 percent and the third column for an assumed polar albedo of 75 percent.

These results show the albedo increasing with month from February through June, but we cannot be sure that this effect is genuine because the radiometer had deteriorated during the life of the satellite. A correction factor determined by Bandeen to be 1.84 beyond March 15 was applied to the data. We cannot be sure that the spectral response did not change so as to create a spurious increase in the global albedo with time.



Emergent Intensity

$$I(\theta, \psi, \zeta)$$

Apparent Reflectance

$$R = \frac{\pi I}{F_o \cos \zeta}$$

True Reflectance

$$\bar{R} = \frac{1}{\pi} \int_0^{2\pi} \int_0^1 R \cos \theta \, d(\cos \theta) \, d\psi$$

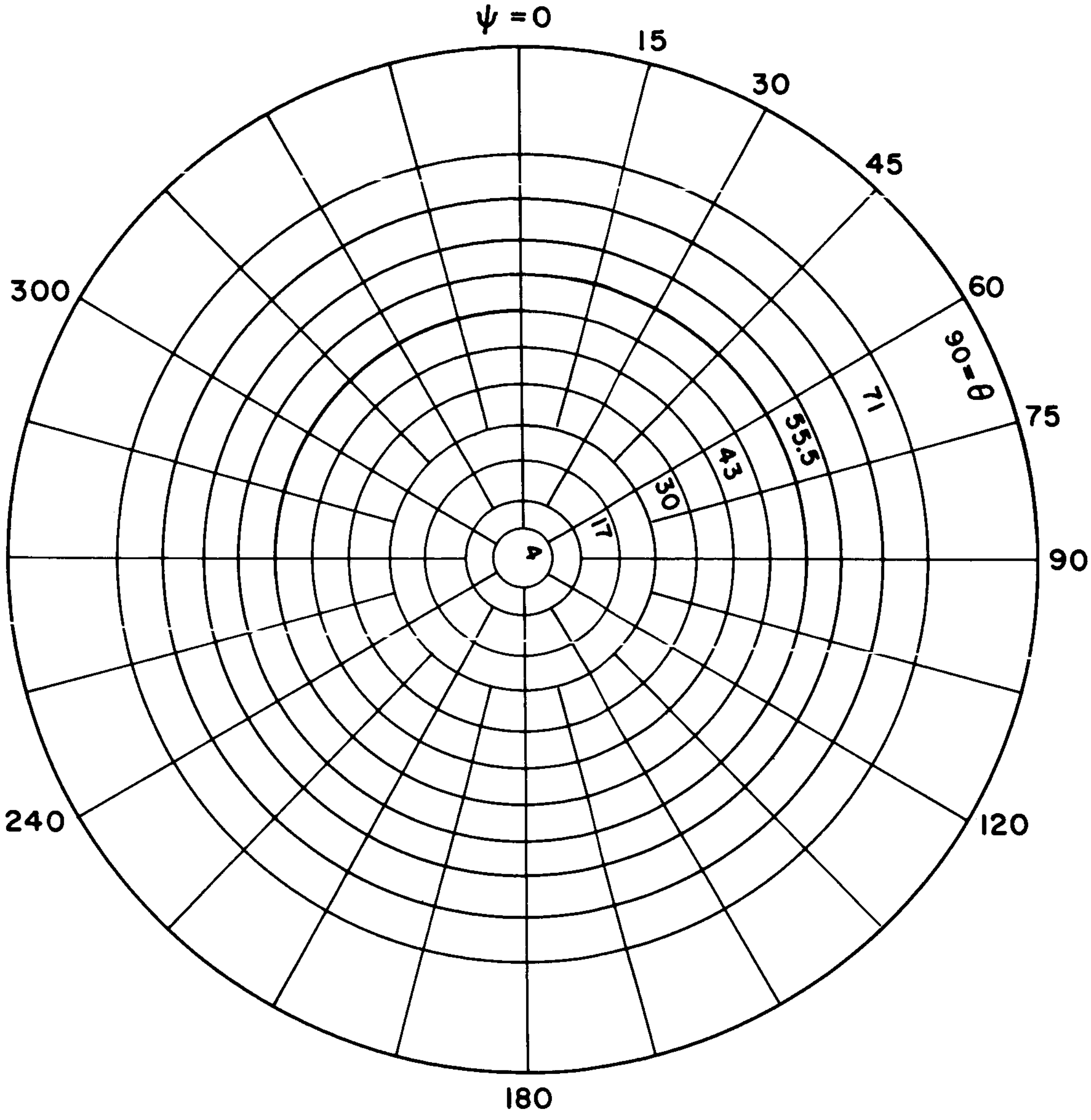
Local Albedo

$$A(\phi, \lambda) = \int \bar{R}(\zeta) W(\zeta, \phi, \delta) \, d\zeta$$

ϕ = Latitude λ = Longitude δ = Solar Declination

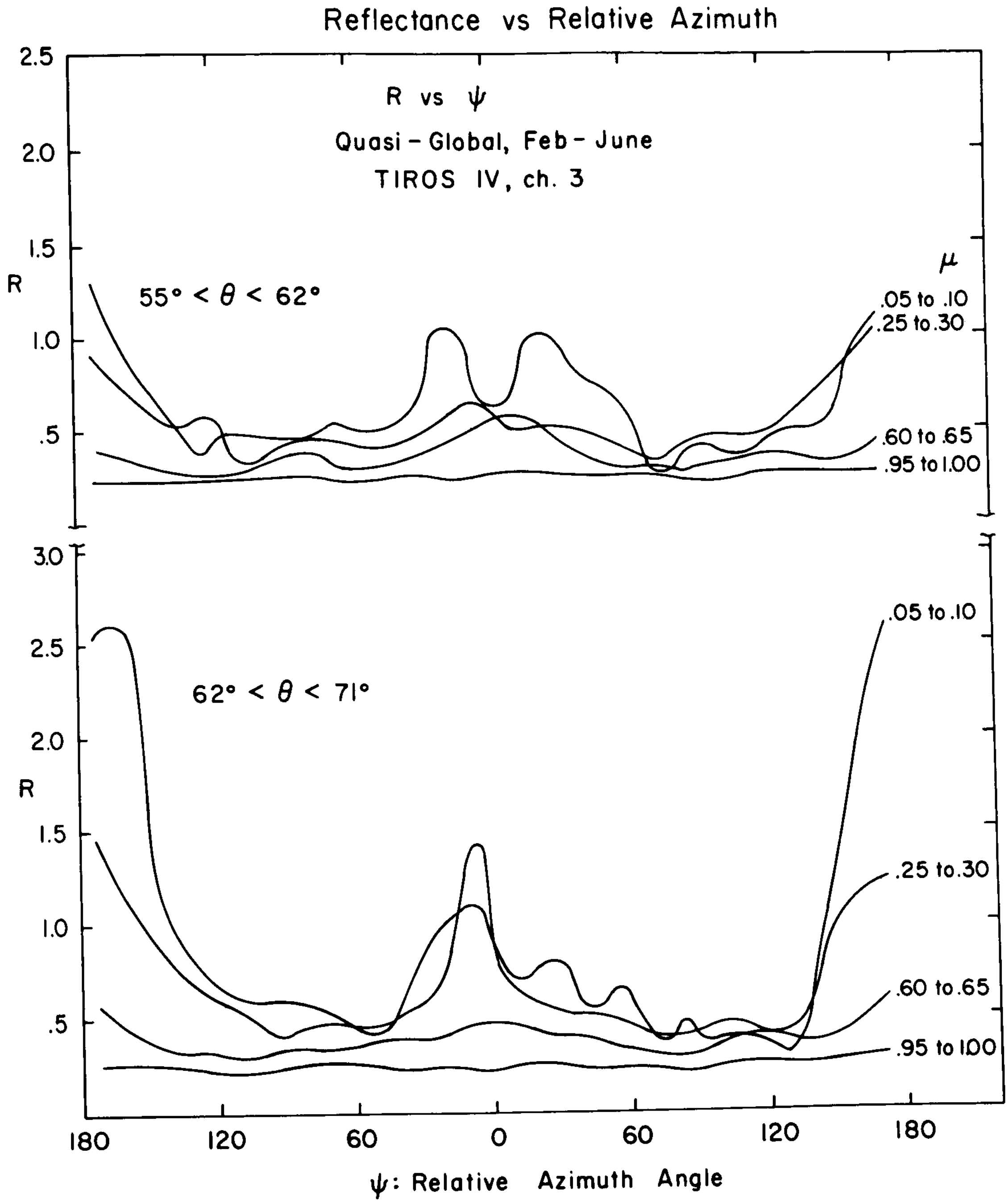
$W(\zeta, \phi, \delta)$ Normalized Solar Energy Weighting Function

Figure 1



ANGULAR DISTRIBUTION GRID

Figure 2



Reflectance vs Relative Azimuth
R vs ψ
Quasi - Global, Feb - June
TIROS IV, ch. 3
55° < θ < 62°
62° < θ < 71°
μ
.05 to .10
.25 to .30
.60 to .65
.95 to 1.00
R
2.5
2.0
1.5
1.0
.5
3.0
180
120
60
0
ψ: Relative Azimuth Angle

Figure 3

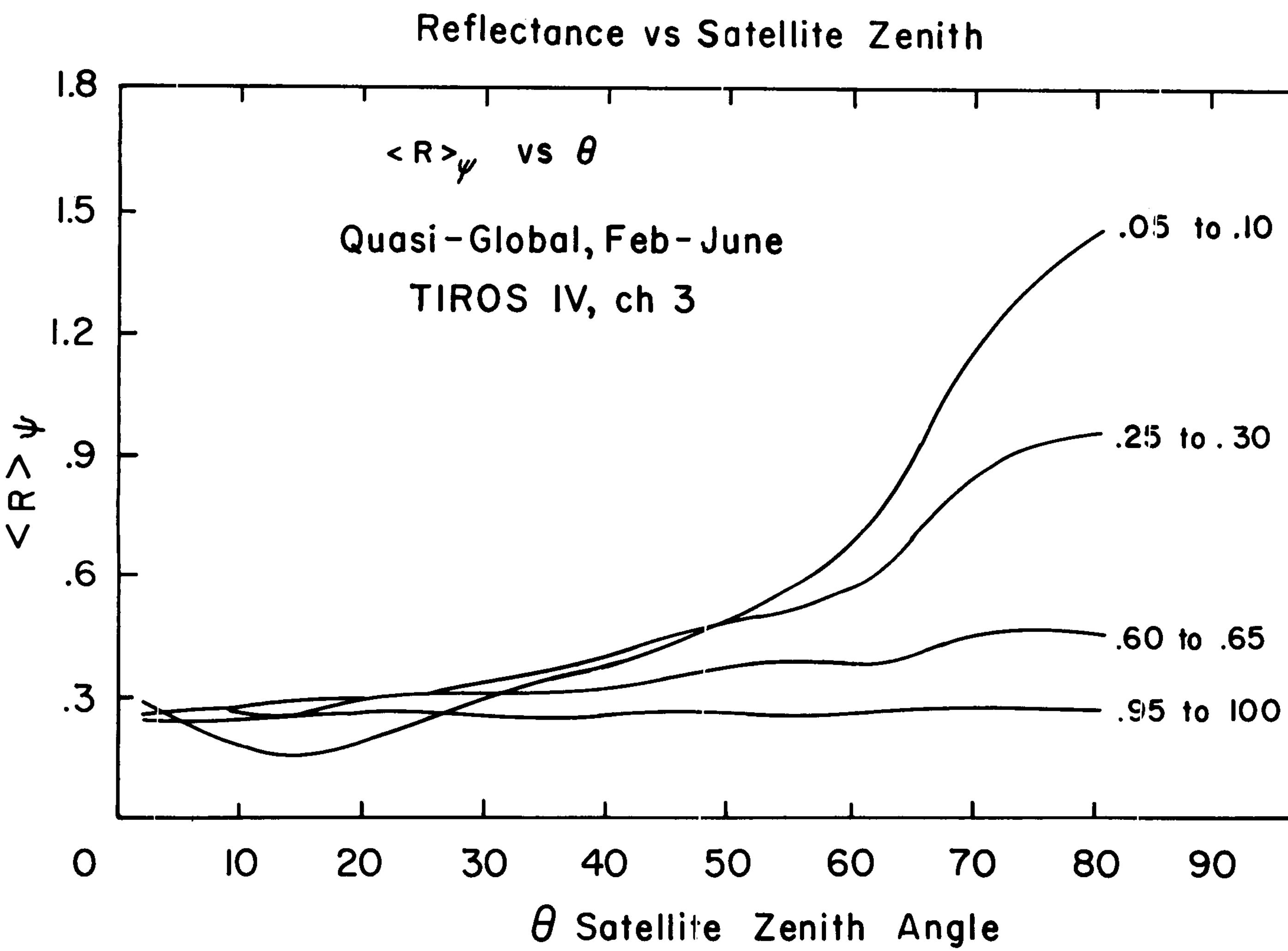
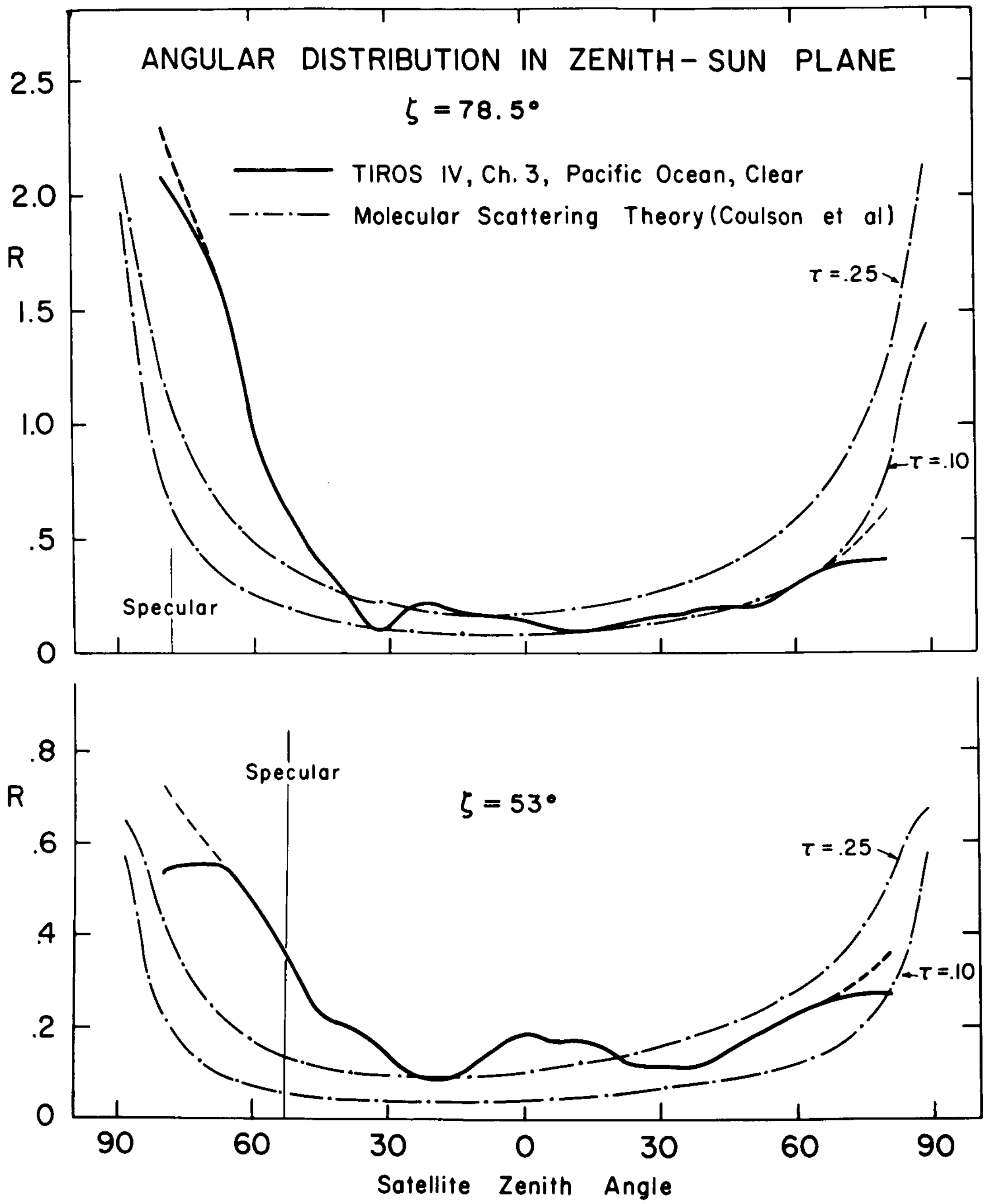

Reflectance vs Satellite Zenith
< R >ψ vs θ
Quasi-Global, Feb-June
TIROS IV, ch 3
.05 to .10
.25 to .30
.60 to .65
.95 to 100
1.8
1.5
1.2
.9
.6
.3
< R > ψ
0
10
20
30
40
50
60
70
80
90
θ Satellite Zenith Angle

Figure 4



ANGULAR DISTRIBUTION IN ZENITH-SUN PLANE
ζ = 78.5°
TIROS IV, Ch. 3, Pacific Ocean, Clear
Molecular Scattering Theory (Coulson et al)
τ = .25
τ = .10
Specular
R
2.5
2.0
1.5
1.0
.5
0
ζ = 53°
.8
.6
.4
.2
90
60
30
0
Satellite Zenith Angle

Figure 5

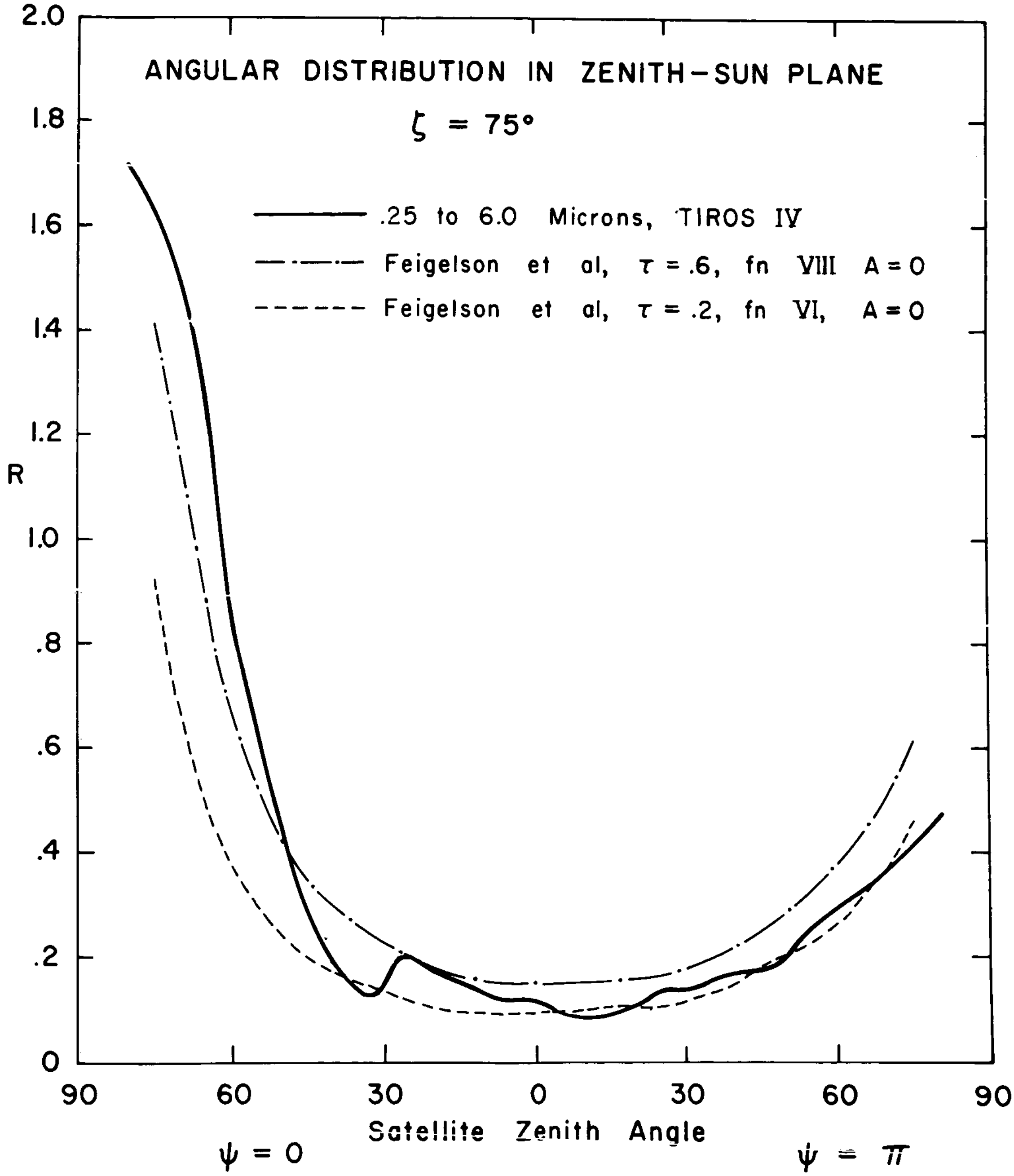
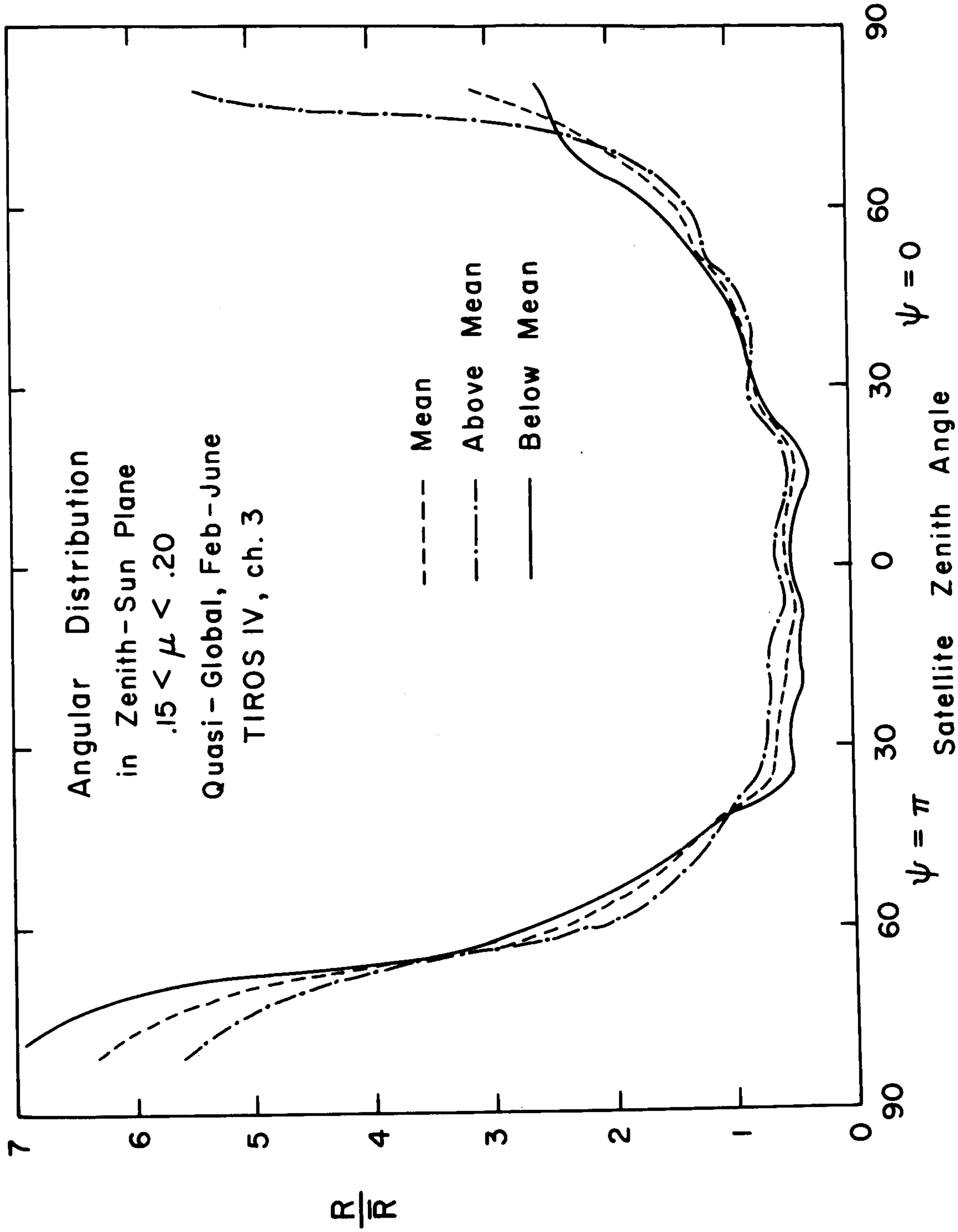

ANGULAR DISTRIBUTION IN ZENITH-SUN PLANE
ζ = 75°
.25 to 6.0 Microns, TIROS IV
Feigelson et al, τ = .6, fn VIII A = 0
Feigelson et al, τ = .2, fn VI, A = 0
2.0
1.8
1.6
1.4
1.2
R
1.0
.8
.6
.4
.2
0
90
60
30
0
30
60
90
Satellite Zenith Angle
ψ = 0
ψ = π

Figure 6



Angular Distribution
in Zenith-Sun Plane
.15 < μ < .20
Quasi-Global, Feb-June
TIROS IV, ch. 3
Mean
Above Mean
Below Mean
R/R̄
0
1
2
3
4
5
6
7
90
60
30
0
30
60
90
ψ = π
ψ = 0
Satellite Zenith Angle

Figure 7

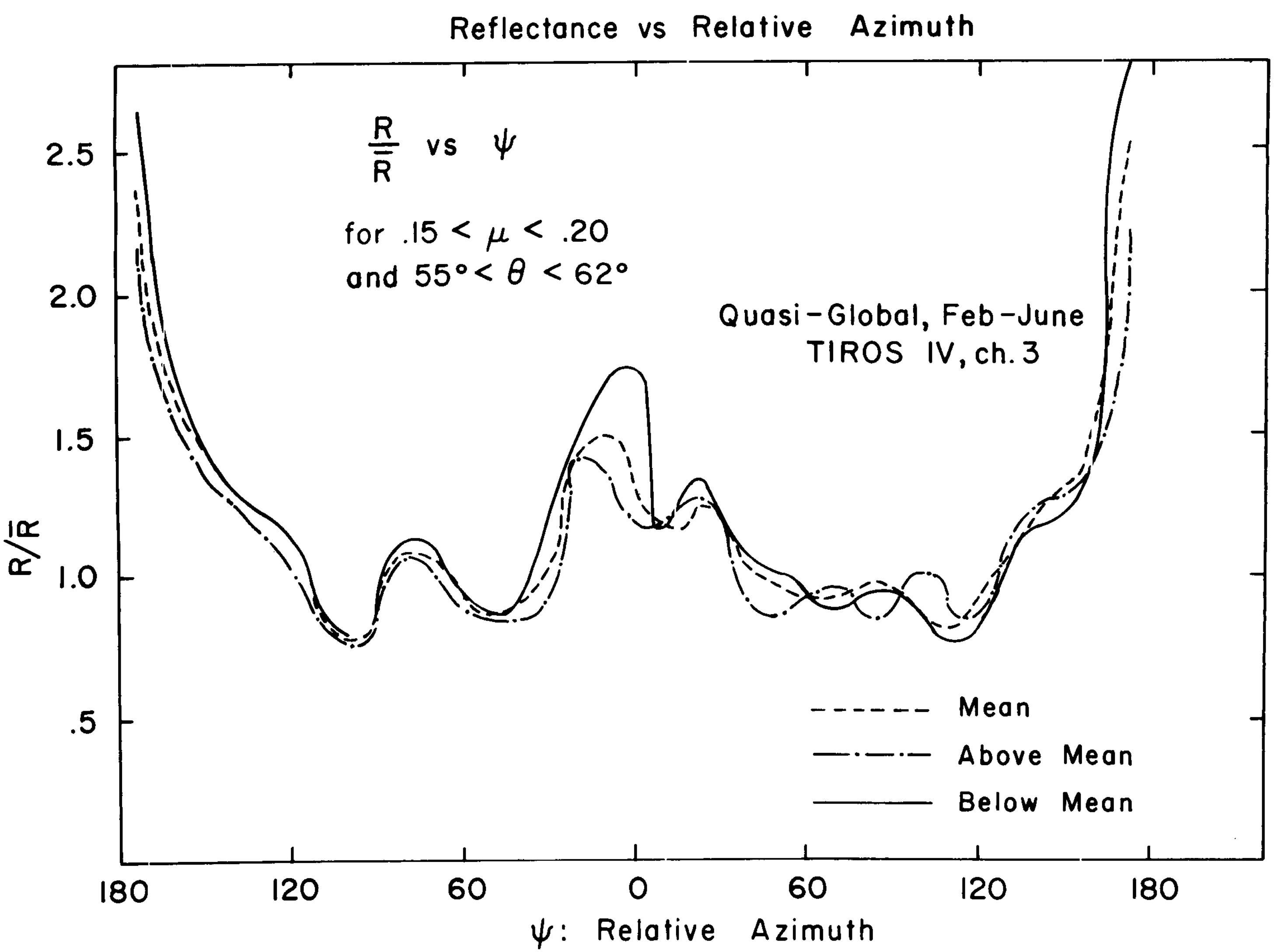

Reflectance vs Relative Azimuth
R/R̄ vs ψ
for .15 < μ < .20
and 55° < θ < 62°
Quasi-Global, Feb-June
TIROS IV, ch. 3
Mean
Above Mean
Below Mean
R/R̄
2.5
2.0
1.5
1.0
.5
180
120
60
0
60
120
180
ψ: Relative Azimuth

Figure 8

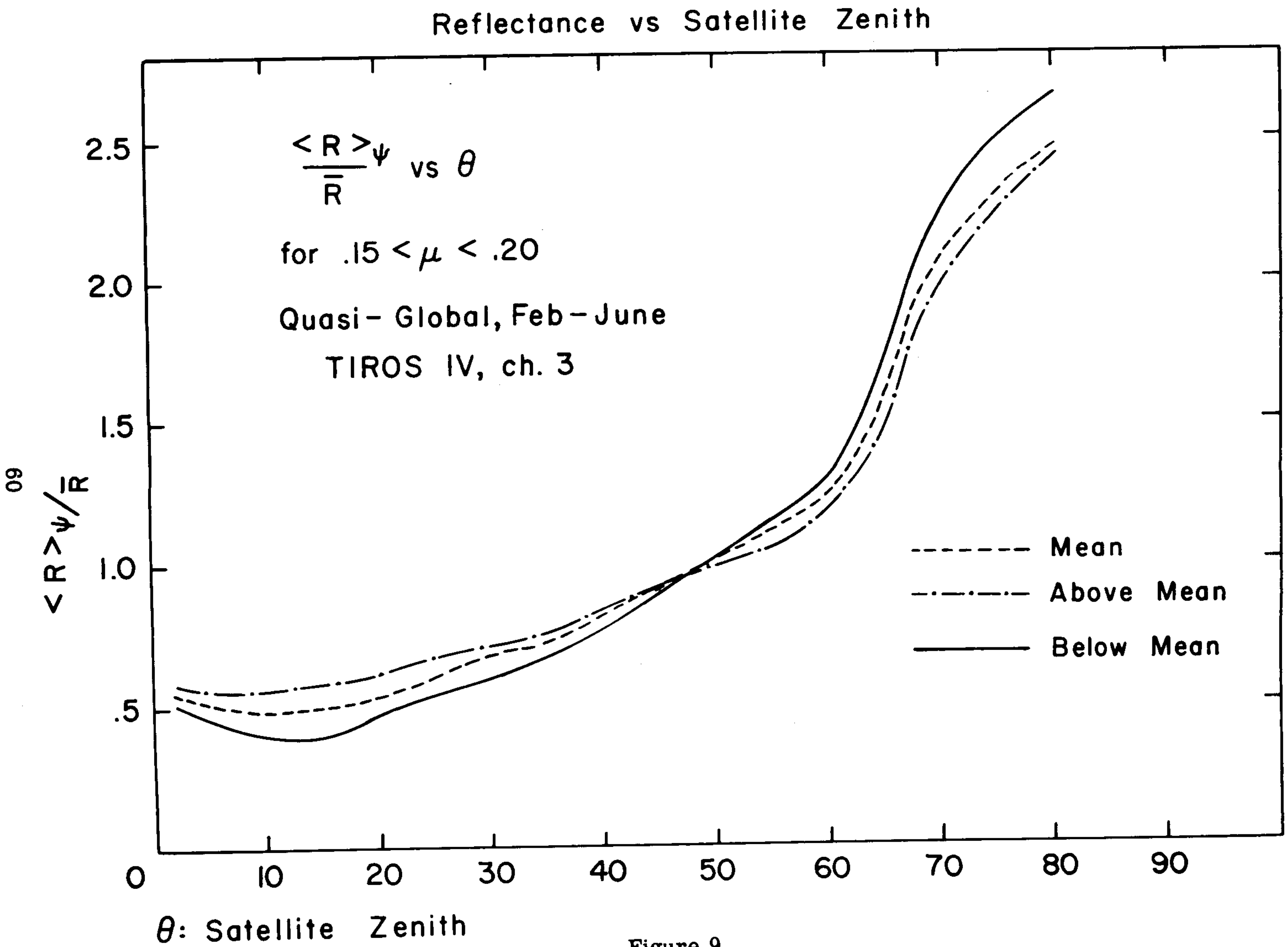

Reflectance vs Satellite Zenith
$\frac{\langle R \rangle_\psi}{\bar{R}}$ vs θ
for $.15 < \mu < .20$
Quasi- Global, Feb-June
TIROS IV, ch. 3
Mean
Above Mean
Below Mean
$\langle R \rangle_\psi / \bar{R}$
2.5
2.0
1.5
1.0
.5
0
10
20
30
40
50
60
70
80
90
θ: Satellite Zenith

Figure 9

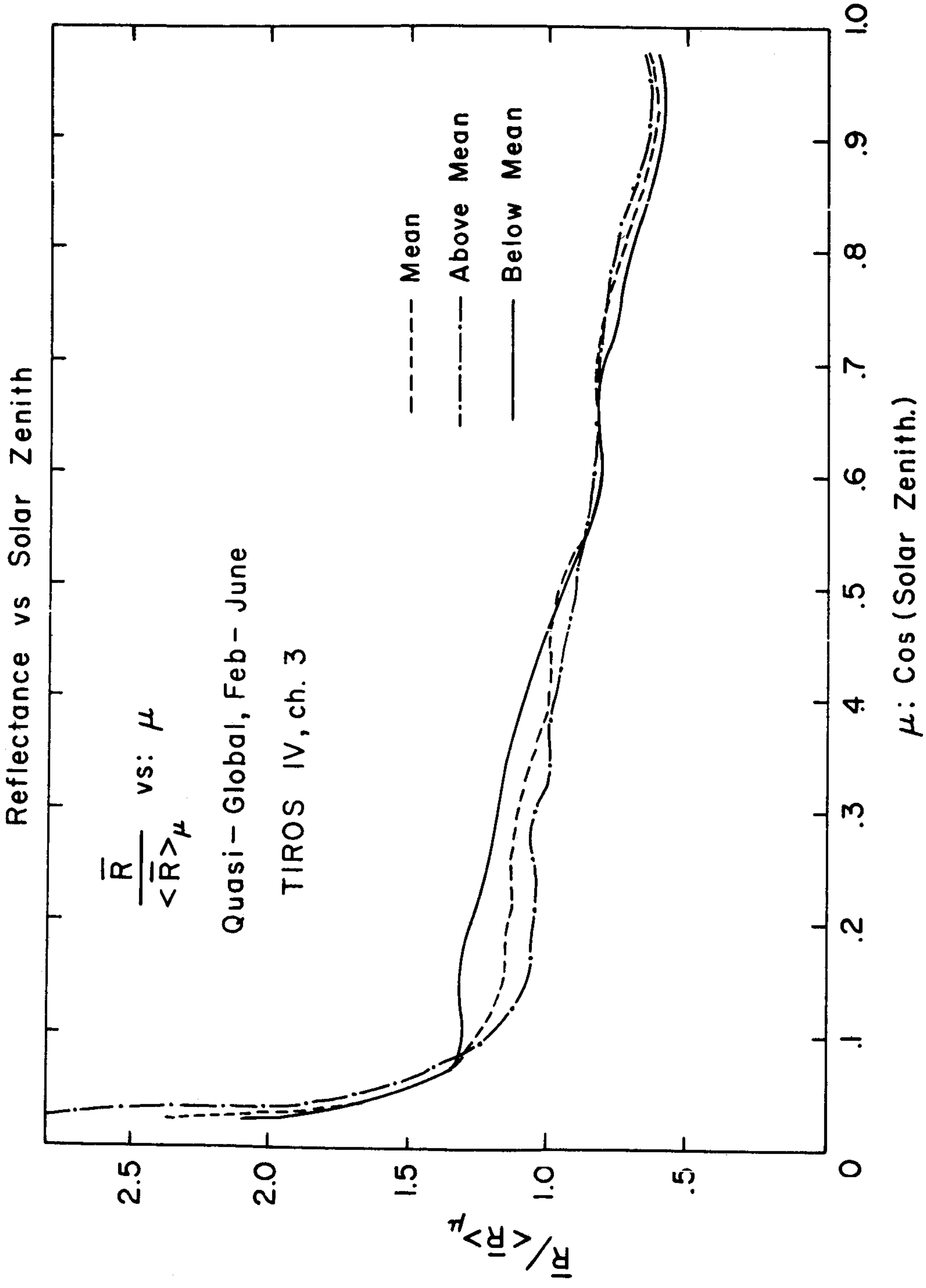

Reflectance vs Solar Zenith
$\frac{\bar{R}}{\langle \bar{R} \rangle_\mu}$ vs: μ
Quasi - Global, Feb - June
TIROS IV, ch. 3
Mean
Above Mean
Below Mean
$\bar{R}/\langle \bar{R} \rangle_\mu$
2.5
2.0
1.5
1.0
.5
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
μ: Cos (Solar Zenith.)

Figure 10

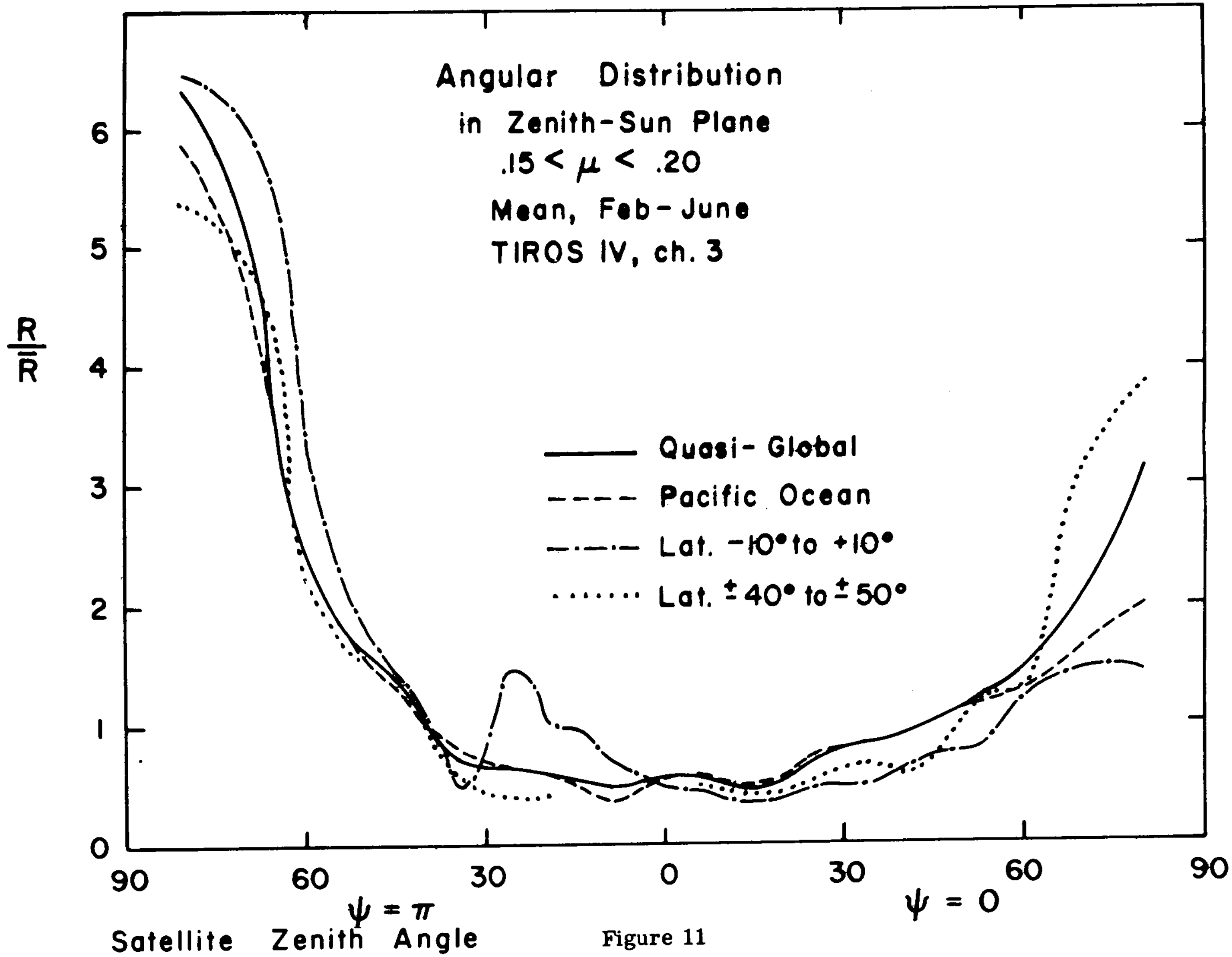
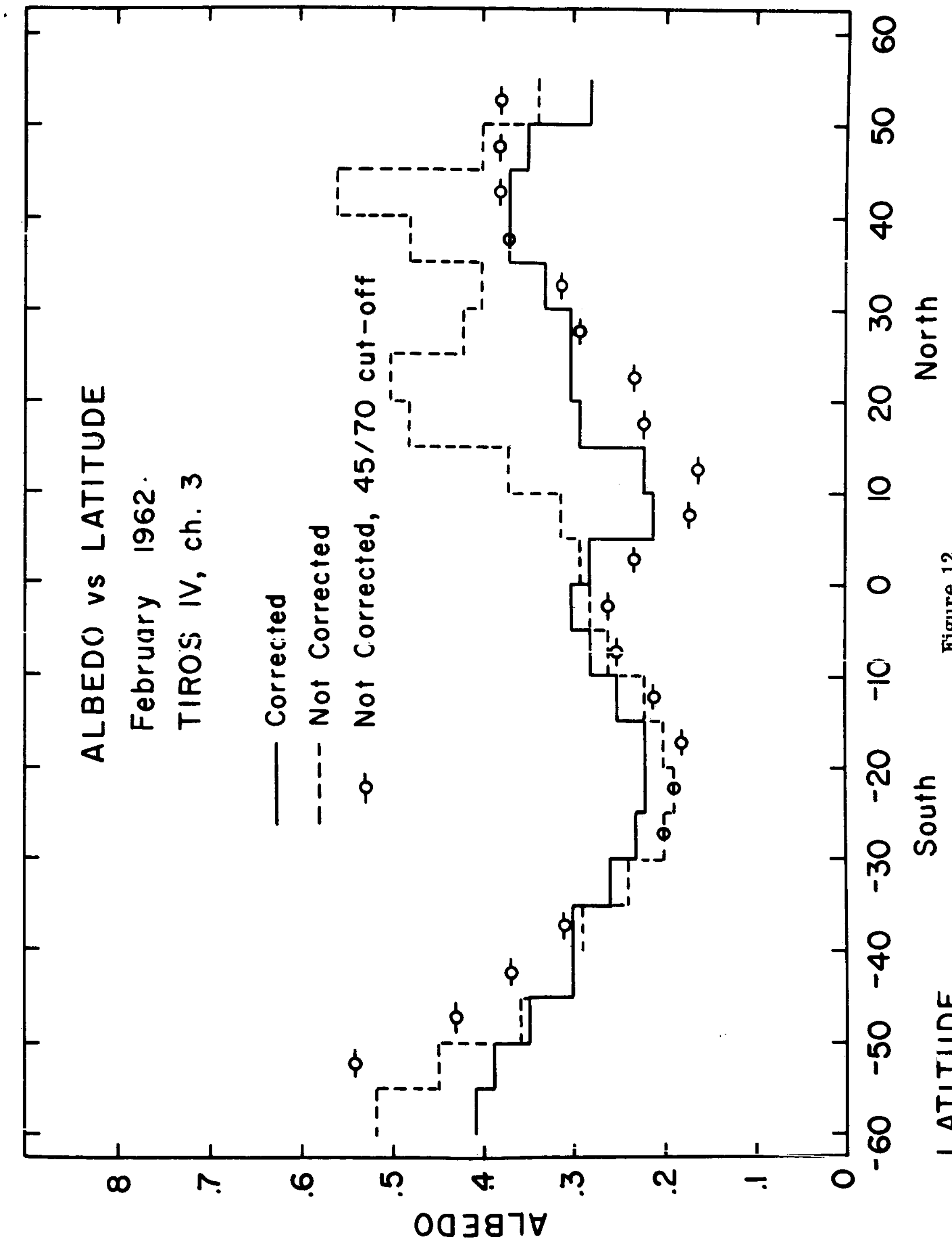

Angular Distribution
in Zenith-Sun Plane
.15 < μ < .20
Mean, Feb-June
TIROS IV, ch. 3
Quasi-Global
Pacific Ocean
Lat. -10° to +10°
Lat. ± 40° to ± 50°
R/R̄
0
1
2
3
4
5
6
90
60
30
0
30
60
90
ψ = π
ψ = 0
Satellite Zenith Angle

Figure 11



ALBEDO vs LATITUDE
February 1962
TIROS IV, ch. 3
Corrected
Not Corrected
Not Corrected, 45/70 cut-off
ALBEDO
0
.1
.2
.3
.4
.5
.6
.7
.8
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
60
South
North
LATITUDE

Figure 12

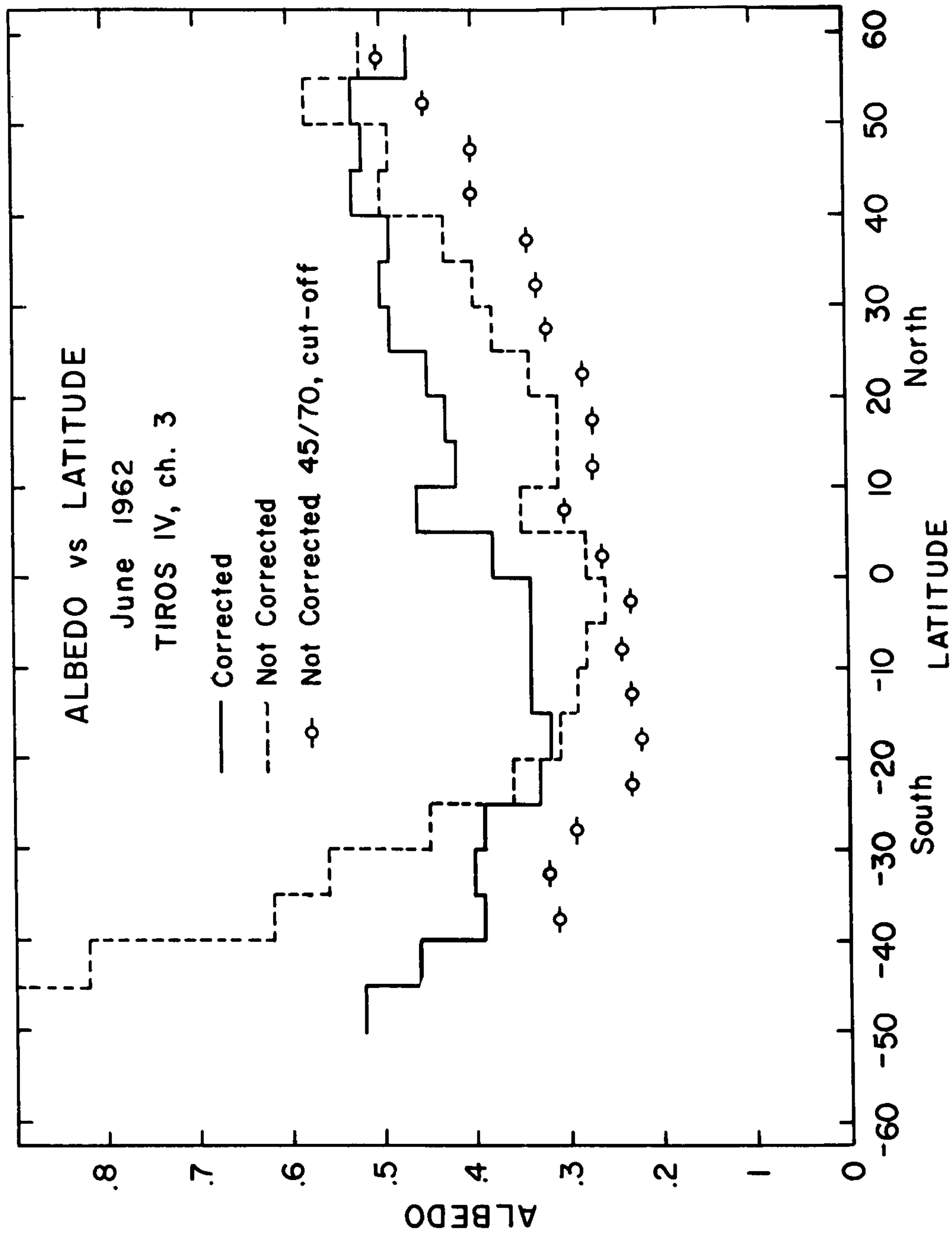

ALBEDO vs LATITUDE
June 1962
TIROS IV, ch. 3
Corrected
Not Corrected
Not Corrected 45/70, cut-off
ALBEDO
0
.1
.2
.3
.4
.5
.6
.7
.8
LATITUDE
South
North
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
60

Figure 13

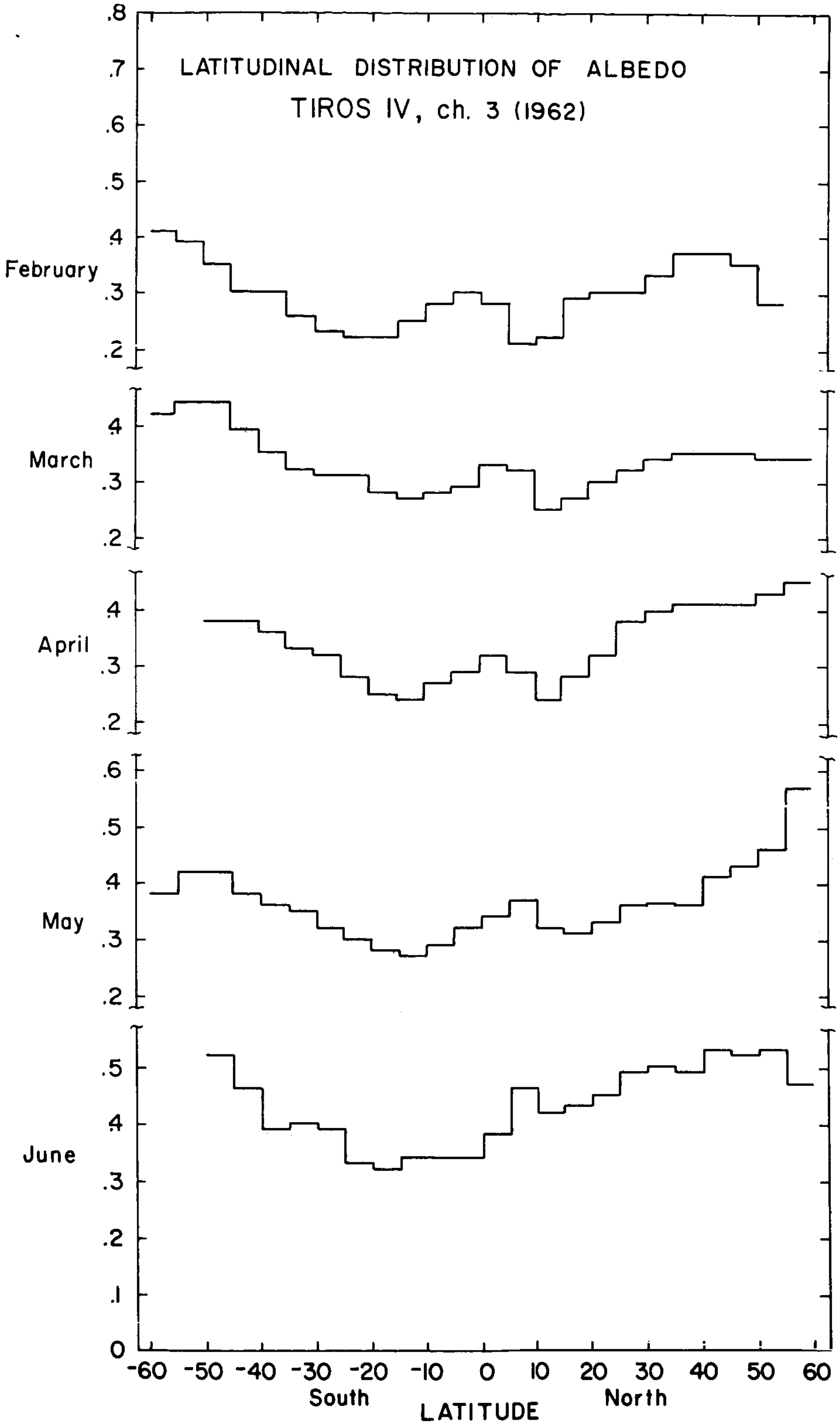

LATITUDINAL DISTRIBUTION OF ALBEDO
TIROS IV, ch. 3 (1962)
February
March
April
May
June
.8
.7
.6
.5
.4
.3
.2
.1
0
-60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60
South
LATITUDE
North

Figure 14

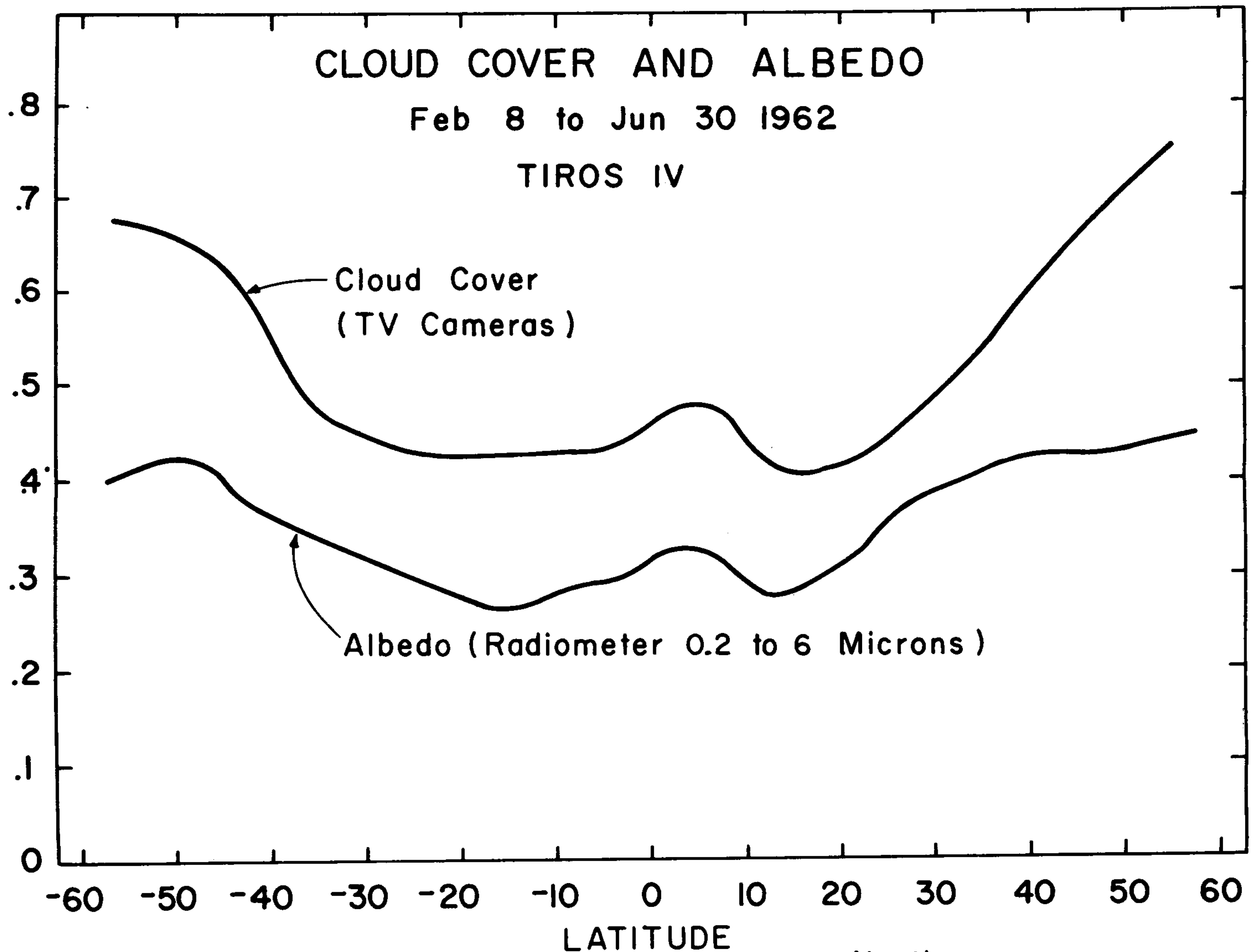

CLOUD COVER AND ALBEDO
Feb 8 to Jun 30 1962
TIROS IV
Cloud Cover
(TV Cameras)
Albedo (Radiometer 0.2 to 6 Microns)
.8
.7
.6
.5
.4
.3
.2
.1
0
-60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60
LATITUDE
South
North

Figure 15

ALBEDO

	-60° to +60°	GLOBAL(1)	GLOBAL(2)
FEB.	.29	.32	.35
MARCH	.32	.35	.38
APRIL	.33	.36	.39
MAY	.35	.37	.41
JUNE	.42	.43	.47
MEAN	.34	.37	.40

ASSUMED ALBEDO FOR POLAR REGION: (1) .50 (2) .75

Figure 16

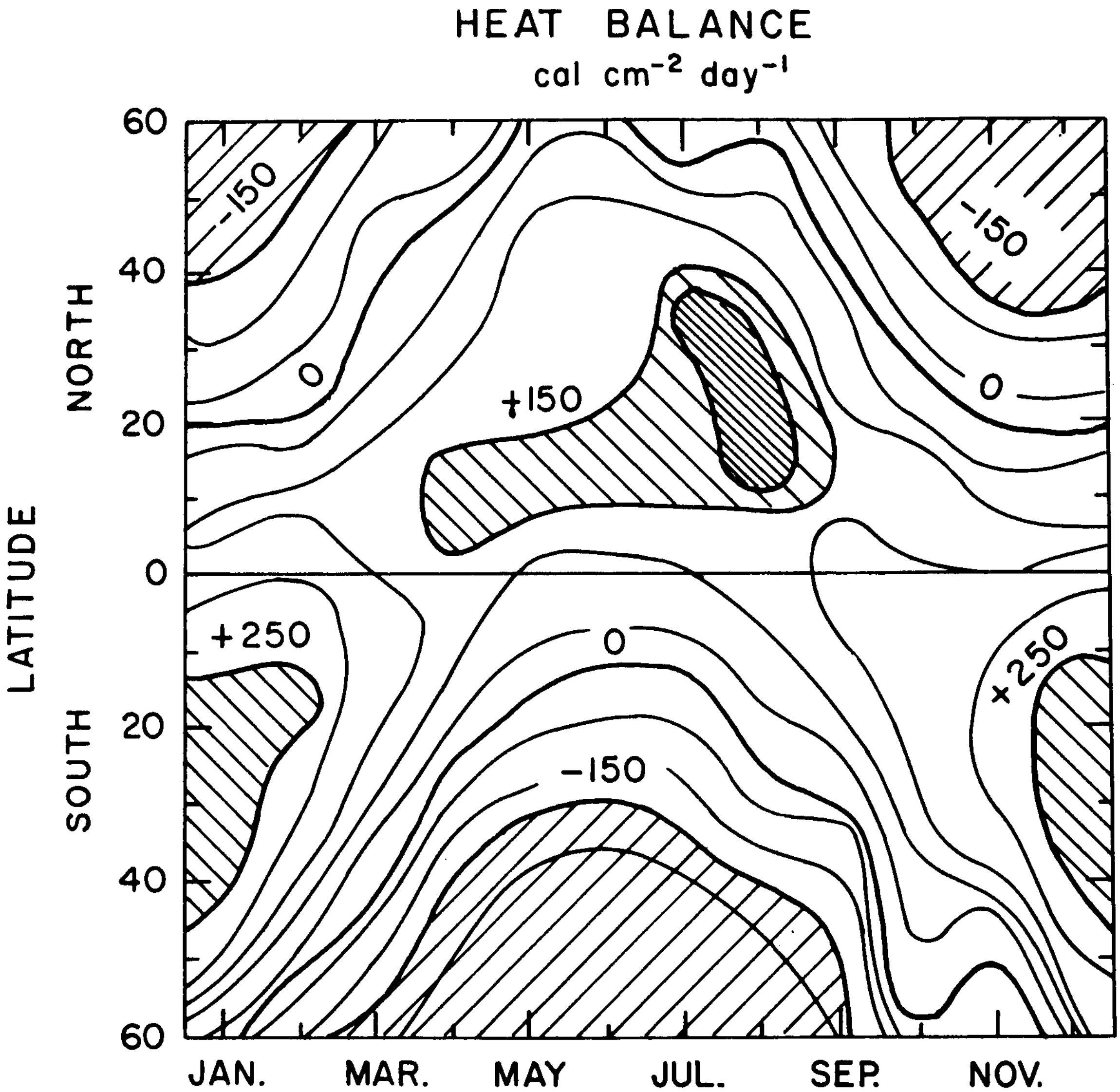

HEAT BALANCE
cal cm-2 day-1
LATITUDE
NORTH
SOUTH
60
40
20
0
20
40
60
-150
-150
0
0
+150
+250
+250
0
-150
JAN.
MAR.
MAY
JUL.
SEP.
NOV.

Figure 17

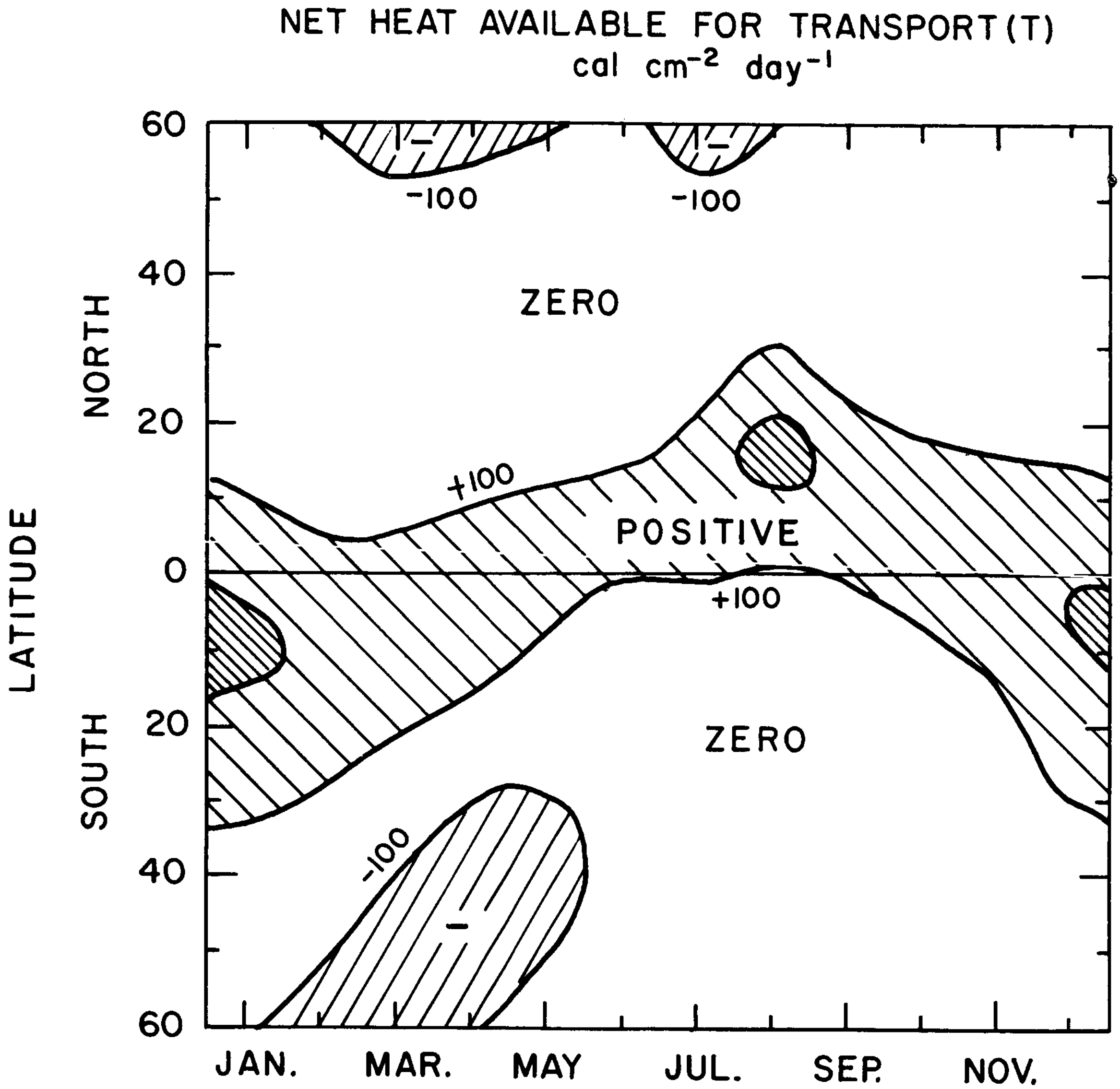

NET HEAT AVAILABLE FOR TRANSPORT (T)
cal cm⁻² day⁻¹
60
40
20
0
20
40
60
NORTH
SOUTH
LATITUDE
-100
-100
ZERO
+100
POSITIVE
+100
ZERO
-100
JAN.
MAR.
MAY
JUL.
SEP.
NOV.

Figure 18

RADIOMETRIC OBSERVATIONS FROM AIRCRAFT DC8 FLYING POLE TO POLE, FALL 1965

S. I. Rasool

The purpose of the experiment is to make absolute measurements of the solar radiation as reflected by the clouds and the earth's surface. The observations will be made continuously by means of a calibrated pyroheliometer looking down from the aircraft for 42 hours while the plane goes around the world from pole to pole. This will give, for the first time, a continuous measurement of the albedo of the various types of clouds, oceans and terrain from the Arctic to the Antarctic, and will also help calibrate radiation measurements of TIROS VII. This satellite is still functioning, but the instrumental response of its radiometers has degraded considerably.

OXYGEN ABSORPTION IN THE MESOSPHERE

P. Thaddeus

A theoretical study has been completed of the emission of thermal microwaves by the 0_2 fine structure lines near a wavelength of 1/2 cm, taking into account the Zeeman effect produced by the earth's magnetic field. The hope is that these lines can be used for future microwave experiments with meteorological satellites to determine the mesospheric temperature on a daily and global basis. The weighting functions calculated using the Goddard Institute's computer for three of the strongest transitions. The weighting function w(z) is normalized so that if the physical temperature is T(z) the observed brightness temperature for an observer looking at the atmosphere from above is

$$T_B = \int_0^{\infty} T(z)\, w(z)\, dz$$

The most important thing to note is that the weighting functions are reasonably sharp and that they peak near 70 km-well into the mesosphere. It is believed that no other lines exist in any other spectral region which can be used to study the thermal structure of the atmosphere at such high altitudes. The results of this theoretical work are being prepared for publication.

NIMBUS MICROWAVE EXPERIMENT

P. Thaddeus

A microwave experiment will be carried aboard either the Nimbus B or the Nimbus D meteorological satellite. These satellites are in roughly polar orbits at an altitude of 1100 km, and are earth oriented at all times. They are scheduled to be launched in two to three years.

The first experiment will be a mapping radiometer designed to measure the brightness temperature of the earth at a wavelength of 1.55 cm, and with a resolution of about 40 km-comparable to the medium resolution infrared radiometer carried by Nimbus. The radiometer is a small radiotelescope which must satisfy very stringent demands by the usual standards of radio astronomy. The specifications for this instrument have been written after a very thorough survey of the present situation with regard to possible electronic components, and evaluation of the several types of systems which could be employed.

The Nimbus experiment has taken about one-third of the research effort during the last six months, and inevitably will require a considerably larger fraction during the coming two or three years. A very large theoretical program to make sense out of the great quantity of data which will be acquired will have to be undertaken in parallel with the construction of the instrument.

ULTRAVIOLET EXPERIMENT ON NIMBUS II

(scheduled flying date, Fall 1966)

S. I. Rasool

A small apparatus will be flown on Nimbus II to obtain a continuous measure of the total intensity in the near ultraviolet region of the solar spectrum over a period of a few months. The experiment will permit one to determine, for the first time, the changes in the intensity of the near ultraviolet radiation during times of solar activity. This in turn will provide the first direct information on the relation between anomalous changes in solar activity and conditions in the lower atmosphere.

The near ultraviolet, 1700-3000 Å, is responsible for the formation of the ozone layer in the upper stratosphere and for the secondary temperature maximum at 50 km. Any sudden or long-period change in intensity in this ultraviolet region will affect the equilibrium of the ozone layer, which may in turn affect the temperature distribution of the stratosphere, producing a wide-scale meteorological repercussion.

Recent observations suggest that a coupling between the upper and lower atmosphere does exist. However, a feasible mechanism is yet to be found which could explain the amplification of the relatively small energy changes, if any, in the solar radiation into large-scale meteorological disturbances in the lower atmosphere.

One of the mechanisms by which a link between solar activity and the lower atmospheric phenomena can be established is the influence of solar near ultraviolet flux on the ozone content of the atmosphere; but no definite conclusions can be derived unless the solar near-ultraviolet flux in the spectral band of 1700-3000Å is actually measured, above the ozone layer, above a specified length of time.

Dr. Heath of the Goddard Space Flight Center is working on the experimental aspects of the problem. We hope to fly five photometers which would measure the near ultraviolet flux in five different spectral intervals.

ENERGY BALANCE OF THE ATMOSPHERE AND OCEANS

S. I. Rasool with C. Prabhakara

Radiation data acquired by the TIROS meteorological satellites, for a period of one full year, has been analyzed in order to determine the regional and time variations in the energy balance of the earth and its atmosphere.

The energy balance of the earth-atmosphere system is made up of the difference between the incoming solar radiation, mostly in the visible, and the outgoing terrestrial radiation in the infrared. For the whole globe, over long periods of time (at least a year), this energy balance is zero. This means that on an average the earth is not gaining or losing heat. Over small regions of the earth and for shorter periods of time (weeks or months), the energy balance of the earth-atmosphere system is not necessarily zero. It is generally known to be positive near the equator and negative at the poles. This constitutes the main driving force for the general circulation of the atmosphere and oceans.

Over a given region the net energy excess or deficit of the earth-atmosphere system manifests itself mainly in three different ways: (1) by the change in the heat content of the oceans or land and of the atmosphere, (2) by an increase or decrease in the latent heat, or (3) by transport of energy through ocean and air currents from one region to another.

The following equation expresses the local energy balance of the earth-atmosphere system:

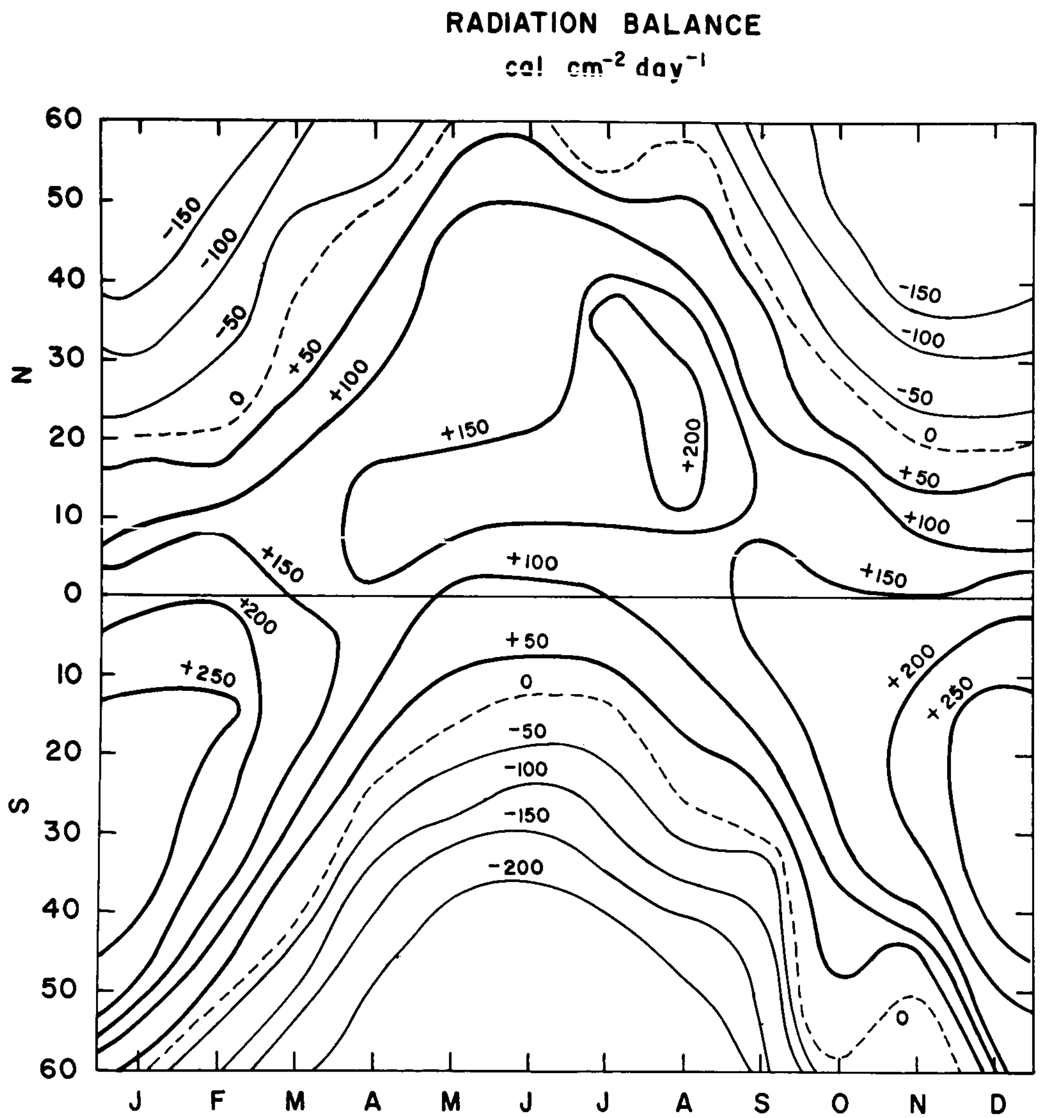
$$R = S + LE + T \qquad (1)$$

where S is the storage of energy which itself has three components: S_O, S_L, S_A, being the storage in oceans, land, and the atmosphere, respectively. Of these, the storage in the oceans is the most significant, and S_L and S_A are usually 10 percent of S_O. LE is the net latent heat available in the atmosphere, being the difference between the amount of energy spent in evaporation of water and that released by condensation in the atmosphere. T is the transport of heat by ocean currents and by winds.

The purpose of this study is to use the data now available from the radiation measurements made by meteorological satellites to derive monthly and latitudinal variations in the net energy available for transport (T) by the atmosphere and by oceans. This is the basic data in understanding the general circulation.

The meteorological satellites are equipped to measure both the reflected solar radiation from the earth and the total infrared radiation emitted by the earth. From the measurement of the part of the solar energy reflected back to the space, we derive the amount of solar radiation which is absorbed by the earth-atmosphere system. The infrared channels of the TIROS satellite, on the other hand, provide estimates of the amount of radiation emitted by the earth-atmosphere system.

Combining the values thus obtained of the incoming and outgoing radiation, we derive monthly averages of the radiative energy balance (R) of the earth-atmosphere system for each 10° latitude belt between 60° N and 60° S. These are plotted in Figure 1. This figure shows the familiar pattern of the positive radiation balance in the subtropical latitudes of the two hemispheres in the local summers.



In order to derive from Figure 1 the net heat available for transport (T), we first estimate the two other parameters of equation (1) which have to be added to the radiation balance in order to get T.

Figure 1

The ocean storage term is estimated by collecting data from all parts of the globe on the variation of ocean temperatures from month to month. Similar computations for the land and atmosphere give estimates of S_L and S_A. The net latent heat (LE) is the difference between the energy spent in evaporation and that which comes back into the atmosphere via condensation. This parameter is also estimated on a global scale from the climatological atlases of evaporation and precipitation. The magnitude of the terms S and LE are fairly large, of the same order as the values of R itself. It is, therefore, not surprising that the derived pattern of the distribution of the transportable heat is very different from that of the radiation balance (Figure 2).

NET HEAT AVAILABLE FOR TRANSPORT

cal cm^{-2} day^{-1}

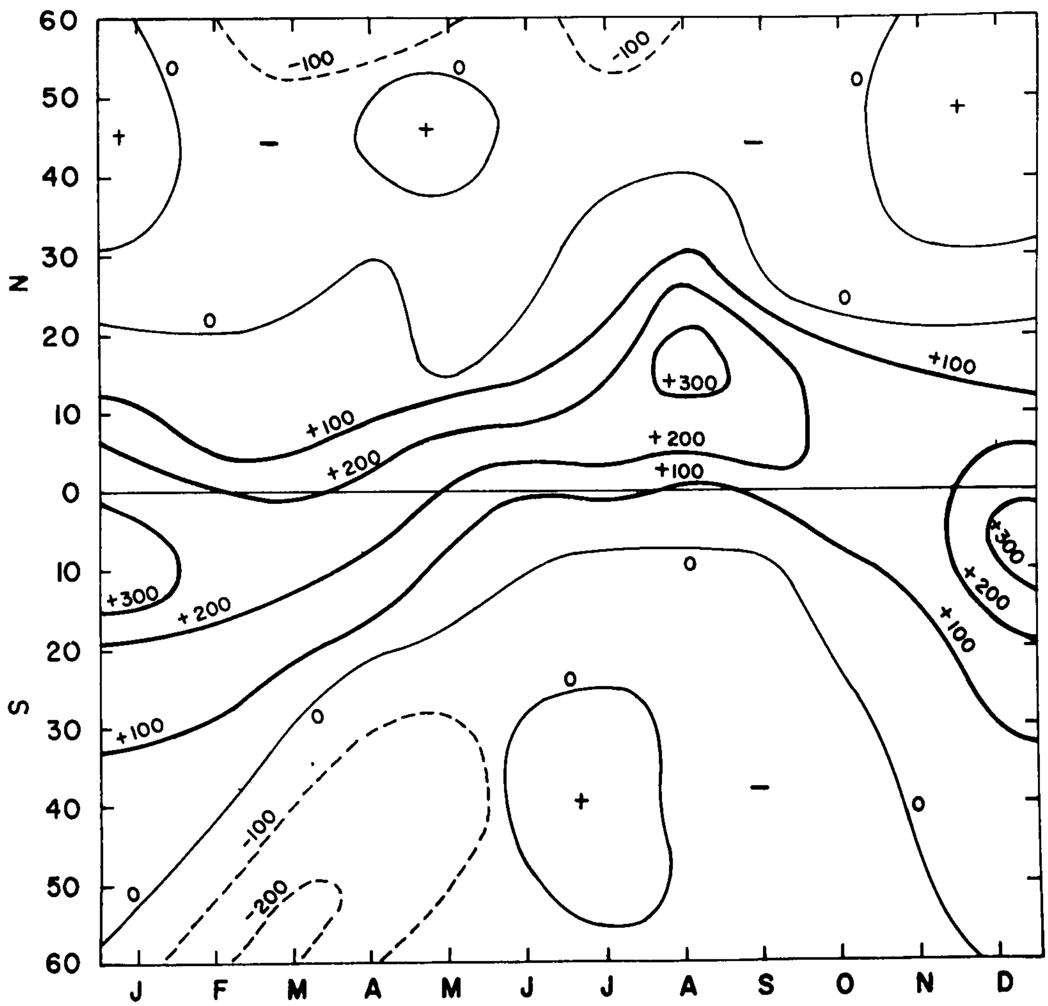


Figure 2

A comparison of Figures 1 and 2 shows that the excesses of energy balance over the middle latitudes in the local summers in Figure 1 have disappeared completely in Figure 2, indicating that none of this heat is available for transport. This is because most of the energy has gone in heating the oceans. The equatorial latitudes, however, still have an excess of energy while the poles show a deficit. This is the imbalance which drives the oceans and the winds. Figure 2 also shows an anomaly in the Southern Hemisphere in the months of February, March and April, where the latitudinal gradient of the transportable energy is much higher than in other months, indicating a maximum southward flux of heat at about 30° S in these months. This is probably due to the anomalous behavior of the Agulhas ocean current which is known to intensify in these months.

Based on Figure 2, the annual transport of heat across latitude circles between 60° N and 60° S is derived. (Figure 3). It is found that the heat flux toward the poles in the Southern Hemisphere is 30% stronger than in the Northern Hemisphere. This is the total heat transported by both the oceans and the atmosphere.

HEAT FLUX TOWARDS POLES

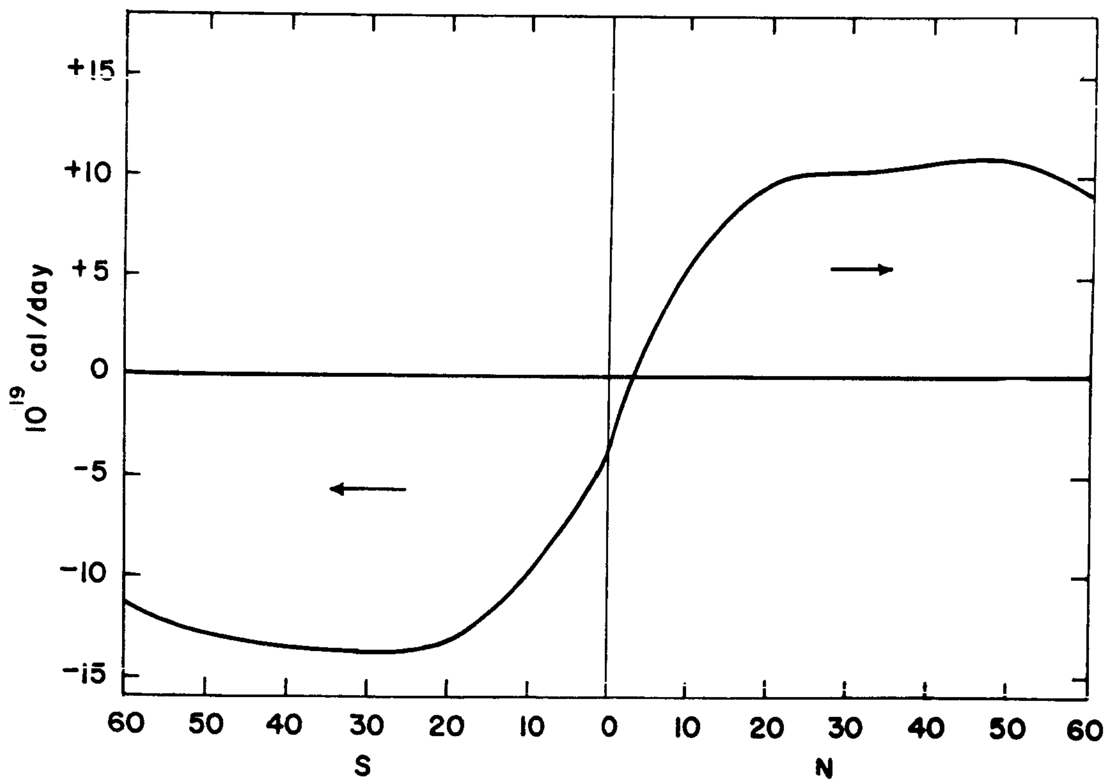


Figure 3

Presently, an attempt is being made to separate the effect of oceans and atmosphere to see if the observed oceanic and atmospheric circulations can be deduced in this fashion. Part of these results were published as a New York University Geophysical Sciences Laboratory Report No. 65-1, January 1965, and also were presented at the COSPAR meeting in Buenos Aires in May, 1965 as "Heat Budget of the Southern Hemisphere." The results will be published in COSPAR proceedings entitled Problems in Atmospheric Circulation, edited by Thomas Malone and R. V. Garcia.

ORIGIN OF PLANETARY ATMOSPHERES

A. G. W. Cameron

Dr. P. Thaddeus has shown from an analysis of microwave processes in the atmosphere of Venus that the atmosphere may be very massive, containing about two orders of magnitude more material than the earth's atmosphere, and that it must be extremely dry, containing neglibible amounts of water. The differences between the atmospheres of Venus and the earth are of great cosmogonic importance and are very challenging from the cosmogonic point of view. In order to account for these differences the following sequence of events has been suggested.

The formation of a planet from the primitive solar nebula should take place by rapid accumulation in the gas before it dissipates to form the sun. As part of this accumulation process it seems likely that the planets should accumulate significant atmospheres from the primitive solar nebula. It is suggested that this is what happened in the case of Venus. The comparative absence of water vapor in the Venus atmosphere should probably be taken to mean that outgassing is a relatively slow process in that planet, so that the outgassed water can be photodissociated, with escape of hydrogen and reaction of the resulting oxygen with the surface materials.

It follows that a similar process should occur for the earth. However, we have independent evidence that the earth's atmosphere is virtually completely derived by outgassing processes from the interior. Therefore, any primitive atmosphere of the earth acquired from the primitive solar nebula would have to be lost into space. The only feasible mechanism by which this might occur would be a rotational instability of the earth itself.

An attempt has been made to seek a relationship between such a rotational instability and the origin of the moon. If the origin of the moon is to arise in this way, then it is required that the earth when formed was spinning much more rapidly than would be the case for the other planets in the solar system. This would be possible only if the last stage in the accumulation of the earth consisted of the mutual capture of two bodies of comparable size when they spiralled together owing to the drag of the primitive solar nebular gases. It is assumed that the formation of the sun then gave rise to a strong solar wind which dissipated the solar nebula, while, shortly after, the formation of the iron core of the earth decreased the moment of inertia of the earth and induced the rotational instability. This would throw off the primitive atmosphere and also much solid material. The solid material would recede to the Roche limit by tidal interaction, but the efficiency for accumulation of this material into a satellite would be rather low, with destructive collisions being the usual event. The present angular momentum of the solar system can only be accounted for if at least 90% of the thrown-off solid material has been perturbed so that it goes into independent orbit about the sun, and has subsequently either collided with the earth or other planets. This picture also has some interesting subsequent requirements for the earth, since the remaining mantle would have to become fully molten. The subsequent cooling period of the mantle, which will be convecting heat to the surface, might well encompass 10^9 years or more, thus accounting for the fact that no surface rocks have been found remaining from the earliest stage of the earth's history.

MODEL PLANETARY ATMOSPHERES

P. Thaddeus

One phase of an experimental study of microwave absorption in model planetary atmospheres has been virtually completed during the period covered by this report. The CO_2, N_2 atmosphere most usually ascribed to Venus has been studied from −38 to 220 °C (235 to 433 °K) for ten mixing ratios varying from all CO_2 to all N_2. A number of rather difficult experimental problems arising from the wide ranges of temperature and pressure that are of interest have been solved, and the acquisition of a unique cavity microwave spectrometer capable of operating up to pressures of 130 atmospheres, and over temperatures from −80° to 330 °C makes possible a number of investigations of interest to the physics of planetary atmospheres, and to physical chemistry as well.

The microwave property most directly determined from measurements is the loss part of the dielectric constant, ϵ'' as a function of density ρ frequency ν, temperature T, and the fraction of CO_2, f. One finds from a least-square fit of all our observations, using the Goddard Institute's computer

$$e''/o^2\nu = 1.40f^2 + 0.46f(1-f) + 0.017(1-f)^2 (T/273.16)^{-2.11}$$

where o is in Amagat, ν in cm^{-1}, and T in degrees Kelvin.

In atmospheric calculations the absorption coefficient α is usually employed. It is derived from the lossy part of the dielectric constant ϵ'' at a given wavelength by the simple expression $\alpha = 2\pi\epsilon''/\lambda$. The microwave brightness temperature T_B (the quantity directly determined from observation in radio astronomy) for a planet such as Venus surrounded by a CO_2-N_2 atmosphere is then given by the expression

$$T_B = 2T_0\bar{e} \int_1^\infty e^{-(\tau_1+\tau_2)x}dx + T_1 \left(1 - 2\int_1^\infty \frac{e^{-\tau_2 x}}{x^3}dx\right)$$

$$+ 2T_0 \int_1^\infty e^{-\tau_2 x} \left\{ \int_0^{\tau_1} \left[\frac{\tau}{\tau_1}(1-\xi^a) + \xi^a\right]^{1/a} \frac{e^{-\tau x}}{x^2} d\tau \right\} dx$$

where $\epsilon = T_1/T_0$, $a = 2\gamma/(\gamma-1)$-3.11 (γ is the ratio of specific heats), and $\bar{e}$ is the average emissivity of the ground, which is known to be about 0.9 from the recent radar studies of Venus. We have assumed an adiabatic lapse rate from the ground at $T_0 \approx 660°$ K to the top of the cloud deck, $T_1 \approx 260°$ K. τ_1 and τ_2 are then just the opacities, $\tau = \int \alpha(z)dz$, derived in the usual way for these two layers from the measured microwave absorption coefficient.

The integration indicated in Eq. (2) has been performed on the Institute's computer, and very good agreement with all of the radio observations made of Venus to date. Fig. 1 shows the radio observations made through the inferior conjunction of the summer of 1964, together with my best fit curve, which requires the very high ground pressure of 125 atmospheres for an assumed mixing ratio of CO_2 of 5%. It is very difficult to account for the falling-off of the microwave brightness temperature at millimeter wavelengths by any other mechanism, and Fig. 1 constitutes one of the strongest pieces of evidence for high surface pressures on Venus.

Laboratory work is being extended to include mixtures of CO_2 with A, Ne and He, and the effect on the absorption coefficient of traces of water vapor. A program for the study of Jovian atmospheres (NH_3 and CH_4 in He and H_2) is planned.

THEORETICAL STUDY OF PLANETARY ATMOSPHERES

P. Thaddeus

A number of problems concerned with the recent studies of Venus have been attacked during the past year. Concerning the basic questions of the very high opacities in the spectral region from roughly 1-30 microns needed to maintain a surface temperature in the vicinity of 700 °K, it has been shown that for a CO_2, N_2 atmosphere alone the inclusion of the many induced vibration-rotation transitions observed in a number of laboratories gives an effective opacity of 100 or more for ground pressures in excess of 50 atm. Several experiments to verify this can be done, and experimental work of this sort may be undertaken in the coming year.

Also under study is the question of planetary circulation for an object such as Venus which seems to have no water vapor, and a very massive atmosphere, and is now known from the radar studies to rotate very slowly. Since both the input and output flux of power are in principle capable of rather precise measurement, the hope is that the primitive equations of motion can be integrated using a reasonable amount of machine time. This work in particular could make excellent use of future infrared radiometry using a large reflecting telescope.

THE UPPER ATMOSPHERE OF JUPITER

S. I. Rasool with S. Gross

There is conflicting evidence regarding the composition of the atmosphere of Jupiter. Although it is generally accepted that the atmosphere of Jupiter is composed mainly of hydrogen and helium, the relative amounts of these two gases in the atmosphere are highly uncertain. According to Urey, 90% of the atmosphere is composed of hydrogen, and only 10% is helium by volume. Opik, on the other hand, contends that helium is much more abundant then hydrogen; namely, 97% He against only 3% H_2.

The purpose of this study was to investigate the formation of an ionosphere in each of the two instances so that observations of the planet in the radio wavelengths might be used to decide between the two extreme models.

To determine the distribution of electron densities, the thermal structure of the atmosphere was first computed. It was found that the exospheric temperature of the planet in both cases was as low as ~ 140 °K (Figure 1). This considerably smaller

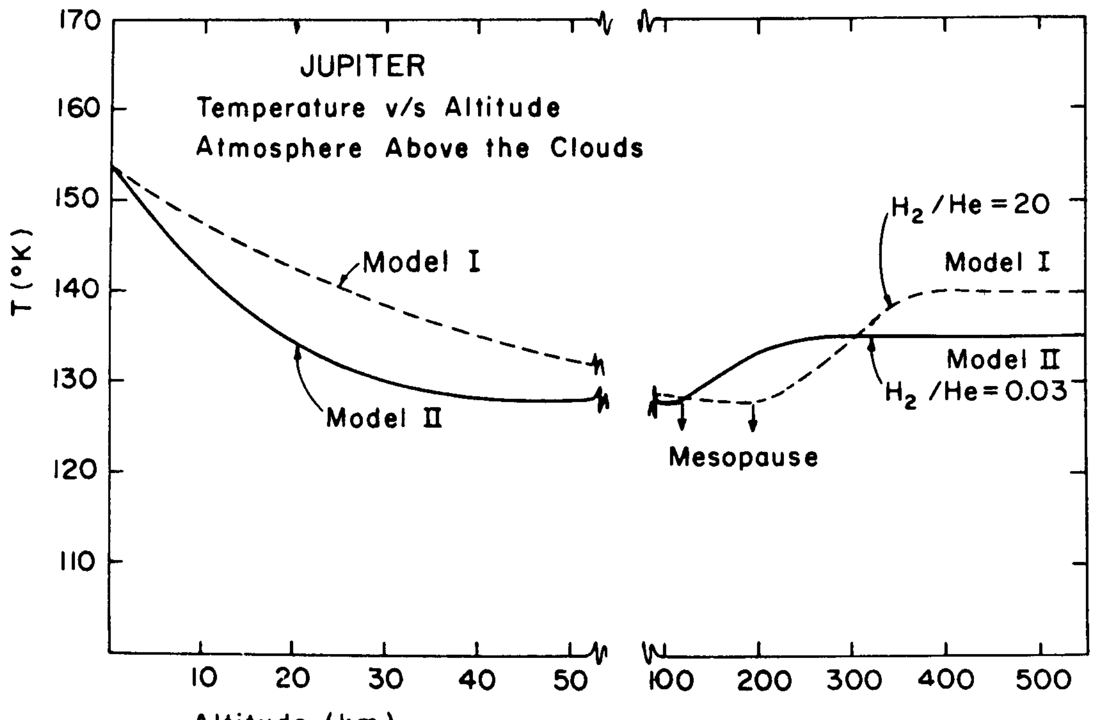


Figure 1

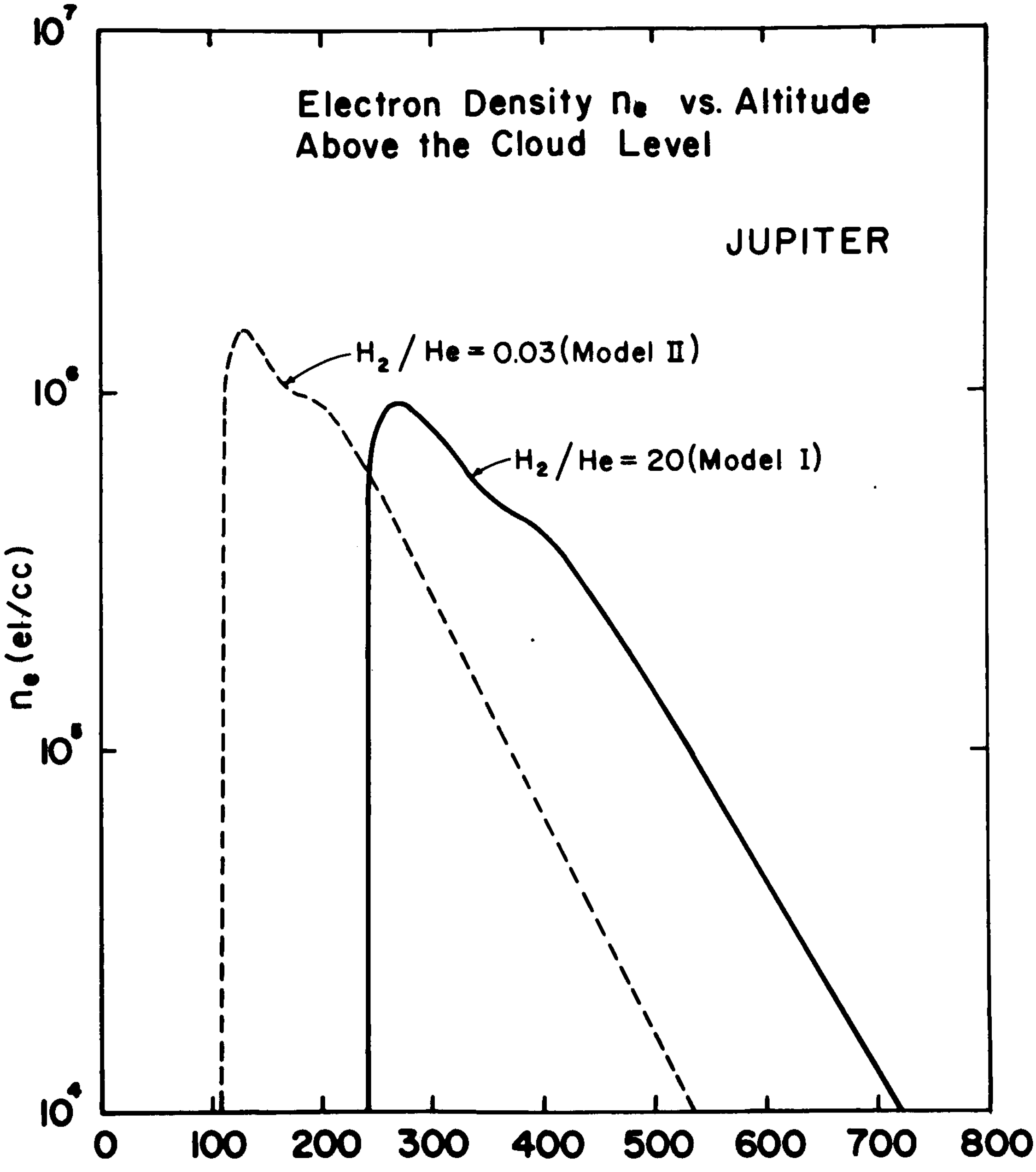
increase in temperature on Jupiter, as compared with the exospheric temperature of the Earth, which is of the order of 1500° K, is the result of the following factors: (1) the intensity of solar radiation at Jupiter is 27 times less than at the distance of the Earth; (2) the conductivity for the gaseous mixture on Jupiter is higher than for the O_2-N_2 mixture for the Earth, and (3) the density scale heights in the upper atmosphere are ~ 5 times less than in the upper atmosphere of the Earth.

In calculating the thermal structure of the planet's atmosphere it was also found that the amount of radiation emitted by Jupiter in the infrared may be ~ 4 times higher than the solar radiation received by the planet.

The ionospheric calculations indicate that the maximum electron density in both cases will be of the order of 10^6 electrons/cc found at an altitude of ~ 160 or ~ 300 km above the clouds, depending on whether He or H_2 is the main component of the atmosphere (Figure 2).

The results of this study on the electron density distribution of the planet may have an important bearing on the validity of those hypotheses which invoke the ionosphere of Jupiter as a direct participant in the generation of decameter radiation. For example, a mechanism has recently been proposed which required electron densities of the order of 10^8 cm^{-3} in the Jovian ionosphere.

Our results on the structure of the Jovian atmosphere were recently published in a paper entitled "The Upper Atmosphere of Jupiter," by S. H. Gross and S. I. Rasool, Icarus, 3, 311, 1964.



Electron Density n_e vs. Altitude Above the Cloud Level
JUPITER
H_2 / He = 0.03 (Model II)
H_2 / He = 20 (Model I)
10^7
10^6
10^5
10^4
n_e (el/cc)
0
100
200
300
400
500
600
700
800
Altitude (Z) km

Figure 2

THE ATMOSPHERE OF MERCURY

S. I. Rasool with S. Gross and W. McGovern

Recent polarimetric measurements of the planet Mercury indicate the presence of an atmosphere of a total pressure of approximately 1 mb. Field has suggested that this could be made up entirely of Argon.

Our theoretical investigations show that for a pure Argon atmosphere, the exospheric temperature of Mercury will be in excess of 5000° K. At this high temperature, the "escape" flux of argon is so large that all argon should have escaped in time $\ll 10^{10}$ years. For the gas to be retained up to the present time, the temperature of the exosphere of Mercury must be $< 1400°$ K. This would necessitate the presence of polyatomic gases to "cool" the exosphere.

The problem has been illuminated by recent Russian findings of the presence of trace amounts of CO_2 on Mercury. We have therefore carried out calculations regarding the effect of the presence of CO_2 on the temperature of the upper atmosphere of Mercury. It is known that at high altitudes CO_2 dissociates into CO and both these molecules radiate strongly in the infrared and thereby cool the exosphere. J. Chamberlain has shown this to be probably the case for Mars.

Our calculations indicate that the presence of CO_2 and CO in the upper atmosphere does decrease the temperature of the exosphere, and for an atmospheric composition of 90% Ne and 10% CO_2, the exospheric temperature of Mercury could be as low as 900° K. At this low temperature both Neon and Oxygen will be stable against thermal escape.

These results were presented at the American Geophysical Union meeting in Washington in April 1965.

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"Planetary Atmospheres and the Origin of the Moon," to be published in The Earth-Moon System, B. G. Marsden and A. G. W. Cameron, eds., Plenum Press.

"Composition of Matter in Nuclear Statistical Equilibrium at High Densities," to be published in The Canadian Journal of Physics, (with S. Tsuruta).

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Stephen P. Maran and A. G. W. Cameron, eds.,
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R. F. Stein and A. G. W. Cameron, eds.,
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IV. CONFERENCE AND LECTURE PROGRAMS

CONFERENCE ON NUCLEOSYNTHESIS

January 25-26, 1965 A. G. W. Cameron, Chairman

SESSION I

- H. E. Suess: Difficulties with theories of nucleosynthesis in stars.
- G. Wallerstein: Observational evidence concerning nucleosynthesis.
- W. L. W. Sargent: Observations of abundance anomalies in magnetic variable stars.
- W. P. Bidelman: Comments on peculiar A stars.
- P. S. Conti: Abundances in metallic line stars.
- H. L. Helfer: Problems Associated with the production of scandium.
- H. Reeves: I. Thermonuclear reaction rates.
  II. Current research at Orsay.

SESSION II

- I. Iben: Stellar evolution through helium burning.
- R. Stothers: Evolution of a 30 solar mass star.
- J. Faulkner: Evolutionary state of peculiar A stars.
- H. Y. Chiu: The approach to supernova implosion conditions.
- A. G. W. Cameron; A. Gilbert, C. J. Hansen, and J. W. Truran: Statistical properties of nuclei and the approach to nuclear statistical equilibrium.
- S. Tsuruta: Equilibrium composition of matter at high densities.
- S. A. Colgate and W. A. Fowler: The nuclear synthesis conditions of Types I and II supernovae.
- D. Arnett: Hydrodynamic implosion calculations.
- J. H. Gibbons: Neutron capture cross section measurements.
- P. A. Seeger: Neutron cross section measurements with nuclear devices.

SESSION III

- D. D. Clayton: Distribution of neutron-source strengths for the s-process.
- P. A. Seeger: Calculations of r-process abundances.
- D. D. Clayton: An experimental test of the Cf^{254} hypothesis.
- G. R. Burbidge: Summary and impressions.

COLLOQUIA AND SPECIAL LECTURES 1964-1965

Oct. 8 "HYDROMAGNETIC WHISTLERS," Tatsuzo Obayashi, Kyoto University, Kyoto, Japan.

Oct. 29 "DYNAMICS OF THE MESOSPHERE," Conway Leovy, RAND Corporation, Santa Monica, California.

Nov. 5 "FLOW OF STRATIFIED AIR OVER MOUNTAINS," Derek Moore, University of Bristol, England.

Nov. 10 "EQUATIONS FOR ADIABATIC COLLAPSE," C. W. Misner, University of Maryland.

Nov. 12 "ON THE ORIGIN OF METEORITES," Edward Anders, Enrico Fermi Institute for Nuclear Studies of the University of Chicago.

Nov. 13 "EFFECTS OF ENERGY TRANSPORT THROUGH TRANSPARENT MEDIA," C. W. Misner, University of Maryland.

Nov. 16 "THE INFLUENCE OF TOPOGRAPHY AND NON-ADIABATIC HEATING ON STATIONARY STATE OF CIRCULATION," M. S. Rao, TRAVELERS Research Center, Hartford, Conn.

Nov. 17 "EVIDENCE FOR A SUPERNOVA OF A. D. 1006," Bernard R. Goldstein, Yale University.

Nov. 19 "LONG PERIOD OSCILLATIONS IN THE STRATOSPHERE," Heinz G. Fortak, Institut fur Theoretische Meteorologie, Der Freien Universitat Berlin, Germany.

Dec. 1 "RADIATIVE DIFFUSION," C. W. Misner, University of Maryland.

Dec. 3 "MAGNETISM AND COSMOGONY II," Leon Mestel, Institute for Space Studies.

Dec. 14 "PHYSICAL CONDITIONS IN INTERGALACTIC SPACE," Dennis W. Sciama, University of Cambridge, England.

Jan. 5 "PLANETARY AND LUNAR OBSERVATIONS WITH THE 1,000 FOOT ARECIBO RADAR," Gordon Pettengill, Arecibo Ionospheric Observatory, Puerto Rico.

Jan. 7 "REVIEW OF THE AUSTIN MEETING ON RELATIVISTIC ASTROPHYSICS," A. G. W. Cameron and R. F. Schwartz, Institute for Space Studies.

Jan. 12 "RADIATION OF ALFVEN WAVES BY LARGE IONOSPHERIC SATELLITES: AN ALFVEN PROPULSION ENGINE (APE) IN SPACE," M. A. Ruderman, New York University.

Jan. 14 "INSTABILITIES OF THE ZONAL FLOW IN PRECESSING SPHEROIDS," W. V. R. Malkus, Woods Hole Oceonographic Institution, Massachusetts.

Jan. 15 "GEOMAGNETIC DYNAMICS AND HYDROMAGNETIC INSTABILITIES IN PRECESSING SPHEROIDS," W. V. R. Malkus, Woods Hole Oceanographic Institution, Massachusetts.

Jan. 29 "THE STRUCTURE OF RADIATING SHOCK WAVES IN WARM HYDROGEN," Angelo Skalafuris, Institute for Space Studies.

Feb. 4 "STABILITY OF SHOCK WAVES IN INHOMOGENEOUS MEDIA," Angelo Skalafuris, Institute for Space Studies.

Feb. 18 "WIND-DRIVEN OCEAN CIRCULATIONS," George Veronis, Massachusetts Institute of Technology.

Mar. 18 "OBSERVATIONAL NEUTRINO ASTRONOMY," Raymond Davis, Brookhaven National Laboratory, Upton, New York.

Mar. 25 "TURBULENT CONVECTION," Robert Kraichnan, Institute for Space Studies.

Apr. 8 "ADVANCED PHASES OF STELLAR EVOLUTION," Martin Schwarzchild, Princeton University, Princeton, New Jersey.

Apr. 9 "POSSIBLE OBSERVATIONAL TESTS OF COSMOLOGICAL THEORIES," Dennis W. Sciama, University of Cambridge, England.

Apr. 15 "PHYSICAL PROCESSES IN THE 26 MONTH OSCILLATION OF THE MESOSPHERE," Richard S. Lindzen, University of Washington.

Apr. 21 "ON THE INTERPRETATIONS OF THE SOLAR ULTRAVIOLET SPECTRUM," Stuart R. Pottasch, University of Groningen, The Netherlands.

Apr. 22 "ON THE DETERMINATION OF THE CHEMICAL COMPOSITION IN THE SOLAR CORONA," Stuart R. Pottasch, University of Groningen, The Netherlands.

Apr. 22 "DIURNAL TIDES IN THE MESOSPHERE," Richard S. Lindzen, University of Washington.

May 6 "IONOSPHERIC REACTION RATES," Michael J. McElroy, Kitt Peak National Observatory.

May 19 "THE FEASIBILITY OF USING LASER TECHNIQUES FOR INTERSTELLAR COMMUNICATION," Frank Rosenblatt, Cornell University, Ithaca, N.Y.

STAFF LECTURES

ARKING, ALBERT

Angular Distribution of Scattered Radiation and Earth Albedo from Tiros IV, International Radiation Symposium, Leningrad, U.S.S.R., Aug. 5-12.

Computer Requirements in the Space Sciences, Inter-Center Committee on Automatic Data Processing, NASA Ames Research Center, Moffett Field, Calif., Sep. 5.

Observation of Scattered Radiation from Tiros Satellite, New York University - Conference on Optical Properties of Aerosols, Onchiota Conference Center, Sterling Forest, Tuxedo, N.Y., Oct. 17.

Global Distribution of Earth Albedo and Cloud Cover, American Meteorological Society, New York, N.Y., Jan. 26.

Recent Scientific Results of Experiments in Space, University of Missouri, Columbia, Mo., May 13.

Recent Scientific Results of Experiments in Space, St. Louis Bicentennial Space Symposium (sponsored by University of Missouri Space Science Research Center & NASA), St. Louis, Mo., May 14.

CAMERON, A. G. W.

Variations of Geomagnetic Activity with Lunar Phase, Second Benedum Earth Symposium, University of Pittsburgh, Pittsburgh, Pa., Nov. 24.

Helium in the Interstellar Medium, American Astronomical Society, Montreal, Canada, Dec. 30.

Effects of the Symmetry Energy in Atomic Mass Formulas, American Physical Society, New York, N.Y., Jan. 30, (with R. Elkin).

Computers and Space Science, Royal Society of Canada, Vancouver, Canada, Jun. 9.

The Atmospheres of the Planets, Gordon Conference on the Chemistry and Physics of Space, Tilton, N.H., Jul. 2.

CHIU, HONG-YEE

The Present Status of Gravitational Collapse and Theoretical Problems Associated with the Observability of Neutron Stars, COSPAR Annual Meeting, Buenos Aires, Argentina, May 13 & 14.

Pre-Supernova Models, American Astronomical Society Meeting, Montreal, Canada, Dec. 30.

EZER, DILHAN

Early Contraction Phases of Stellar Evolution, The American Astronomical Society, Montreal, Canada, Dec. 28, (with A. G. W. Cameron).

FORTAK, H.

Numerical Filtering of Two-Dimensional Meteorological Fields, American Meteorological Society, University of Minnesota, Minneapolis, Minn., Nov. 13.

GILBERT, A.

A General Formula for Nuclear Level Densities, American Physical Society, New York, N.Y., Jan. 28, (with A. G. W. Cameron).

JASTROW, ROBERT

Research Programs and University Associations at the Goddard Institute, College Federal Agency Council, Monticello, N.Y., Oct. 15.

Why Land on the Moon? The Franklin Institute, Philadelphia, Penna., Jan. 20.

The Origin of the Solar System, Manned Spacecraft Center, Houston, Tex., Mar. 11.

Astrophysics and Planetary Physics, Lewis Research Center, Cleveland, Ohio, Mar. 15.

Prospectus for a Course in Space Science for Secondary School Students, Conference on Science Education for College Science Teachers, Pittsburgh, Penna., Apr. 5.

Lunar and Planetary Physics, University of Rochester, Rochester, N.Y., Apr. 6.

La Science dans l'Espace, Franco-Malagache Circle, Tannanarive, Malagasy, June 4.

The Scientific Significance of Lunar Exploration, University College, Nairobi, Kenya, June 7.

JASTROW, ROBERT (Continued)

Rotation of the Earth, Haile Selassie University, Addis Ababa, Ethiopia, June 11.

LECAR, MYRON

The Continuous Spectrum of an AO Star, International Astronomical Union, Hamburg, Germany, Aug. 25 - Sep. 3.

Convergence of Lambda Iterations, Harvard-Smithsonian Conference on Stellar Atmospheres, Cambridge, Mass., Jan. 20 - 22.

OBAYASHI, TATSUZO

Hydromagnetic Wave Propagation in the Magnetosphere, Terrestrial Magnetism & Atmospheric Electricity Society, Sendai, Japan, Oct. 19.

PRABHAKARA, C.

Equilibrium Temperature Distribution in the Mesosphere and Lower Thermosphere, American Meteorological Society, New York, N.Y., Jan. 28.

RASOOL, S. I.

Physics and Chemistry of the Upper Atmosphere, The National Congress of Vacuum Techniques in Space Research, Paris, France, Jul. 2.

Heat Balance of the Atmosphere and the General Circulation, International Union of Geodesy & Geophysics, International Symposium on Radiation, Leningrad, U.S.S.R., Aug. 7.

Radiation Studies from Meteorological Satellites, American Meteorology Society, New York, N.Y., Jan. 28, (with S. Gross).

The Atmosphere of Mercury, American Geophysical Union, Washington, D.C., Apr. 19 - 22.

Heat Budget of the Southern Hemisphere, COSPAR Meeting, Buenos Aires, Argentina, May 13 - 19.

SCHWARTZ, ROBERT

Gravitational Field Accompanying a Burst of Radiation, 2d Texas Symposium on Relativistic Astrophysics, Austin, Tex., Dec. 19.

STEIN, ROBERT

The Effects of Penetrative Convection on Lithium, American Astronomical Society, Montreal, Canada, Dec. 28, (with D. Ezer and A. G. W. Cameron).

THADDEUS, PATRICK

Atmosphere of Venus, American Astronautical Society, Denver, Colo., Feb. 8.

Millimeter Wave Techniques for Spacecraft Meteorology, Symposium on Millimeter Wave Techniques in Space Exploration, Cambridge, Mass., May 28.

The Atmosphere of Venus, Gordon Research Conference on the Chemistry & Physics of Space, Tilton, N.H., Jun. 28 - Jul. 2.

WALKER, JAMES

Airglow Evidence for a Non-Ultraviolet Ionization Source in the Upper Atmosphere, American Geophysical Union, 45th Western National Meeting, Seattle, Wash., Dec. 30.

V. UNIVERSITY PROGRAMS

Summer Institute in Space Physics

Sixty-five science and engineering students under NASA grants participated in the annual Summer Institute in Space Physics, conducted by Columbia University in cooperation with the Goddard Institute. The program is designed to introduce outstanding college students to principal areas of the national space program. The students were taught the basic theories of atmospheric structures and dynamics; the properties of the atmospheres of Earth, Mars and Venus; the upper atmosphere and the magnetosphere; the evolution of stars and galaxies; radio astronomy, and the origin of the elements. Students in the engineering option also took courses in rocket propulsion, guidance and control, scientific satellites, communications and manned space flight.

Five weeks of lectures were followed by visits to NASA facilities at Huntsville, Ala.; Cape Kennedy, Fla.; Hampton, Va.; Greenbelt, Md., and NASA Headquarters in Washington.

Students for the program, selected in a nationwide competition, came from 42 colleges in 20 states. Five of the participants were women. Sixteen students represented universities in 11 foreign countries: Canada, Denmark, England, France, Germany, Italy, Nigeria, the Netherlands, Republic of China, Spain and Sweden. Five other foreign students from England, Nigeria and the Republic of China attended universities in the United States. The program was directed by Robert Jastrow.

Summer Institute in Space Science and Engineering

The engineering option of the Summer Institute in Space Physics was expanded into a full-fledged parallel program of 1965. For the first annual Summer Institute in Space Science and Engineering, 30 undergraduates were awarded NASA grants for six weeks of training in rocket propulsion, plasma physics, space communications and aerospace dynamics.

Summer Faculty Program in Space Physics

A new program of professional training in the space sciences for faculty members of American universities was begun in the summer of 1965 as an in-service institute of Columbia University. The NASA-sponsored program is under the direction of A. G. W. Cameron, member of the Goddard Institute staff and adjunct professor of physics at New York University. The purpose of the program is to survey the research problems of the greatest current interest in the space sciences, and to provide the training necessary for undertaking this research. Twelve participants who held doctorates in the physical sciences were selected in a nationwide competition for the seven-week course of lectures, seminars and research colloquia. Topics included fluid dynamics, elasticity, high energy and plasma physics and thermonuclear reactions.

Summer High School Program in Space Physics

Forty-eight students were selected from 300 applicants in the New York metropolitan area to participate in an introductory summer program in the space sciences at the high school level.

DOCTORAL THESES BASED ON RESEARCH COMPLETED AT THE GODDARD INSTITUTE

ARNETT, D.

"Physical Processes and Supernova Dynamics," submitted June, 1965, Graduate School, Yale University, Physics Dept., degree to be conferred June, 1966, (sponsored by A. G. W. Cameron).

GILBERT, A.

"Nuclear Reactions in the Late Stages of Stellar Evolution," submitted Spring, 1965, Graduate Faculty of Pure Science, Columbia University, final defense of dissertation to be in November, 1965, (sponsored by A. G. W. Cameron).

LOMAZZO, A.

"Neutrino Pair Emission from Electron-Electron Scattering," submitted May, 1964, Graduate faculties of Columbia University, 1964, Degree conferred December, 1964, (sponsored by H. Y. Chiu).

TRURAN, J.

"Thermonuclear Reactions in Supernova Shock Waves," submitted June, 1965, Graduate School, Yale University, Physics Dept., degree to be conferred June, 1966, (sponsored by A. G. W. Cameron).

TSURUTA, S.

"Neutron Star Models," submitted June, 1964, Graduate Faculty of Pure Science, Columbia University, formal defense of dissertation September, 1964, degree conferred October, 1964, (sponsored by A. G. W. Cameron).

WALKER, J. C. G.

"The Day Airglow and the Heating of the Upper Atmosphere," submitted March, 1964, Graduate Faculties, Columbia University, Dept. of Geology, formal defense of dissertation April, 1964, degree conferred June, 1964, (sponsored by R. Jastrow).

COURSES TAUGHT
IN THE METROPOLITAN AREA

CITY UNIVERSITY OF NEW YORK

PRABHAKARA, CUDDAPAH
"Dynamical Meteorology," Spring '65, City College, Physics Department.

SKALAFURIS, ANGELO
"Astronomy," Spring '65, City College, Physics Department.

COLUMBIA UNIVERSITY

CHIU, HONG-YEE
"Weak Interactions and Relativity in Astrophysics," Spring '65, Physics Department.

JASTROW, ROBERT
"Physics of the Atmosphere," Fall '64 - Spring '65, Geology Department.

"Introduction to Space Physics," Spring '65, Astronomy Department.

THADDEUS, PATRICK
"Microwave Physics," Fall '64, Physics Department.

"Seminar in Space Science," Fall '64 - Spring '65, School of Journalism, Sloan-Rockefeller Program in Advanced Science Writing.

THE NEW SCHOOL FOR SOCIAL RESEARCH

EZER, DILHAN
"Astronomy," Fall '64, A Certificate Program in Science, Technology and Civilization, Non-credit and/or undergraduate credit.

NEW YORK UNIVERSITY

ARKING, ALBERT
"Physics of the Upper Atmosphere," Fall '64 - Spring '65, Graduate Division, School of Engineering and Science, Dept. of Meteorology and Oceanography.

CAMERON, A. G. W.
"Astrophysics," Fall '64 - Spring '65, Graduate Division, School of Engineering and Science, Physics Department.

RASOOL, S. ISHTIAQ
"Meteorological Measurements by Rockets and Satellites," Spring '65, Graduate Division, School of Engineering and Science, Dept. of Meteorology and Oceanography.

WALKER, JAMES
"Introduction to Space Physics," Fall '64 - Spring '65, Graduate Division, School of Engineering and Science, Dept. of Aeronautics and Astronautics.

YALE UNIVERSITY

CAMERON, A. G. W.
"Galactic and Stellar Physics," Fall '64 - Spring '65, Graduate School of Arts and Sciences, Physics Department.

LECAR, MYRON
"Galactic Structure," Fall '64 - Spring '65, Graduate School of Arts and Sciences, Astronomy Department.

VI. STAFF

1964 - 1965

Robert Jastrow, Director
A. G. W. Cameron
Hong-Yee Chiu
S. Ishtiaq Rasool
Albert Arking
Patrick Thaddeus
Dilhan Ezer
Myron Lecar

Arthur L. Levine, Executive Officer
Nicholas Panagakos, Public Information Officer
George Goodstadt, Publications Officer

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Heinz Fortak, Free University of Berlin, West Germany.
Johannes Geiss, University of Berne, Switzerland.
Cullen Inman, New York University.
Shoji Kato, University of Tokyo, Japan.
Leon Lucy, Princeton University.
Leon Mestel, University of Cambridge, England.
John Potter, New York University.
Cuddapah Prabhakara, New York University.
Wolfgang Priester, University of Bonn, West Germany.
Hubert Reeves, University of Montreal, Canada.
Albert Salmona, Observatoire de Meudon Service d'Astrophysique, France.
Edwin Salpeter, Cornell University.
Chun-San Shen, University of Maryland.

Angelo Skalafuris, Institut d'Astrophysique, France.
Harold Stolov, City University of New York,.
Richard Stothers, Harvard University.
James Walker, Columbia University.