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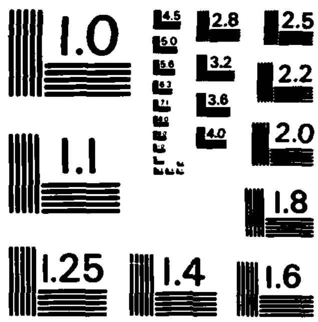

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Earth's Radiation Belts

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28 September 1984

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Prepared for

SPACE DIVISION
AIR FORCE SYSTEMS COMMAND
Los Angeles Air Force Station
P.O. Box 92960, Worldway Postal Center
Los Angeles, Calif. 90009

This report was submitted by The Aerospace Corporation, El Segundo, CA 90245, under Contract No. F04701-83-C-0084 with the Space Division, P.O. Box 92960, Worldway Postal Center, Los Angeles, CA 90009. It was reviewed and approved for The Aerospace Corporation by H. R. Rugge, Director, Space Sciences Laboratory. First Lieutenant Douglas R. Case, SD/YCM, was the project officer for the Mission-Oriented Investigation and Experimentation (MOIE) program.

This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER SD-TR-84-50	2. GOVT ACCESSION NO. AD-A147 927	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) EARTH'S RADIATION BELTS		5. TYPE OF REPORT & PERIOD COVERED
		6. PERFORMING ORG. REPORT NUMBER TR-0084(4940-06)-4
7. AUTHOR(s) M. Schulz		8. CONTRACT OR GRANT NUMBER(s) F04701-83-C-0084
9. PERFORMING ORGANIZATION NAME AND ADDRESS Laboratory Operations The Aerospace Corporation El Segundo, California 90245		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Space Division Los Angeles Air Force Station Los Angeles, California 90009		12. REPORT DATE 28 September 1984
		13. NUMBER OF PAGES 41
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Charged-particle energization
Cosmic rays
Geomagnetically trapped particles
Magnetospheric ion composition
Ring current

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report reviews the status of radiation-belt science at the close of the data-acquisition phase (1976-79) of the International Magnetospheric Study (IMS). The purpose is to place recent discoveries in context with respect to long-standing problems, and to indicate possible directions for future research in radiation-belt physics. The review includes a synopsis of results achieved on topics related to the source, energization, transport, and loss processes that affect geomagnetically trapped radiation, as well as results

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19. KEY WORDS (Continued)

20. ABSTRACT (Continued)

concerning certain subtle consequences of adiabatic charged-particle motion. Major areas of interest include the effects of charge exchange and radial transport on the ion composition of the ring current and radiation belts, the measurement of ion distributions in all three dimensions of velocity space, and the evolution of radiation-belt particle intensities as a consequence of temporal variations of transport coefficients and boundary conditions over the solar cycle and over the course of a magnetic storm. Moreover, the realization is developing that the major uncertainties in radiation-belt physics lie beyond the radiation belts themselves. These uncertainties include (1) the problem of particle energization in the plasma sheet, which defines an outer boundary condition for the ring current and radiation belts; (2) the problem of particle energization in solar flares and in Jupiter's magnetosphere, both of which seem to constitute sources for the earth's radiation belts; and (3) the relationship of large-scale electric- and magnetic-field fluctuations across the magnetosphere to interplanetary parameters and geomagnetic indices that vary with time.

PREFACE

The author is pleased to thank Dr. D. J. Southwood and Dr. C. T. Russell for the invitation that led to preparation of this review.

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INTRODUCTION

This review is supposed to summarize the status of radiation-belt science in the wake (i.e., post-mortem, aftermath) of the data-acquisition phase (1976-79) of IMS, the International Magnetospheric Study. The intent is to provide background and a conceptual framework for operation during the data-analysis phase (1980-85) of IMS. The main thrust of IMS seems to have been directed toward an understanding of magnetosphere dynamics, e.g., the transfer of energy into the magnetosphere and the magnetospheric dissipation of that energy. Although such processes involve plasmas of much lower energy per particle than the radiation belts, they do shed light on possible source and transport mechanisms for radiation-belt particles. Moreover, although the IMS is not primarily a radiation-belt study, it would be wrong to ignore the wealth of radiation-belt data provided by spacecraft such as GEOS, ISEE, and SCATHA. Vette [1980] has compiled an exhaustive directory of spacecraft instruments that were in operation during the data-acquisition phase of IMS.

Progress in radiation-belt science during the IMS period has not been characterized by revolutionary breakthroughs. The concepts underlying radiation-belt science were already in good shape prior to IMS and continue to be in good shape as the data-analysis phase continues. What has developed over the years is a maturity of outlook and a realization that radiation-belt science has progressed from the realm of qualitative empirical description to the stage of quantitative dynamical modeling. This is the context in which the high-resolution data acquired during IMS become important, since quantitative dynamical modeling requires the specification of phase-space density as a function of adiabatic invariants and time. Improved resolution of particle flux as a function of energy and pitch angle yields improved resolution of the phase-space density and (therefore) improved quantitative understanding of radiation-belt dynamics.

An additional requirement for accurate specification of phase-space density is accurate specification of the magnetic field. The field models reviewed by Walker [1979] are representative of progress in this area, but more work remains to be done. Realistic and dynamically self-consistent models of the ring-current contribution to the vector $\underset{\sim}{B}$ field would be especially welcome as a supplement to existing empirical models. Moreover, the effect of magnetopause currents and neutral-sheet currents on the magnetic field, and hence on particle trajectories in the ring current, needs to be considered explicitly in this context.

RECENT PROGRESS

It might be appropriate in a review of the present type to recount in full the accomplishments of radiation-belt science for the 1976-79 time period. However, this will not be done here. The author has already published a review [Schulz, 1980] of radiation-belt papers from the 1977-79 period, and a repetition of that review here would needlessly try the reader's patience. What is offered instead (in this section) is a synopsis of selected highlights from the 1980 review, together with sufficient background material to provide a historical framework and perspective. Subsequent sections provide a look into the future.

A long-standing problem in radiation-belt physics has been to decide whether radiation-belt particles enter the magnetosphere mainly from interplanetary space or mainly from the ionosphere. The IMS has seen evidence building on both sides of the question. The evidence for extraterrestrial sources is seen primarily in the high-energy channels. It has long been recognized [Singer, 1958; Vernov et al., 1959; Kellogg, 1959] that the 50-100 MeV protons which populate the inner radiation zone have as their source the decay of albedo neutrons liberated in the spallation of atomic nuclei in the upper atmosphere by incident cosmic rays. Radiation-belt protons [Farley et al., 1970] and electrons [Lanzerotti et al., 1970] in the 0.1-10 MeV energy range typically show a monotonic increase of phase-space density with L at fixed M and J (adiabatic invariants). This monotonicity suggests inward radial diffusion from an outer boundary at $L \sim 10$ but does not prove that the particles maintaining the boundary condition originate outside the earth's magnetosphere. Many particles clearly do originate one or more astronomical units from the earth, e.g., solar-flare protons seen at synchronous altitude within hours after the flare [Paulikas and Blake, 1969]. One of the provocative ideas to emerge from the IMS period is the suggestion of Baker et al. [1979] that relativistic electrons from Jupiter's magnetosphere [e.g., Krimigis et al., 1975; Mewaldt et al., 1976] help to populate the earth's outer zone at energies $\gtrsim 5$ MeV. A good test for this idea would be to search for a 13-month periodicity in the radiation intensity at these energies in the earth's outer electron belt.

Evidence for an ionospheric source of trapped particles is provided by ion-composition studies. GEOS observations reported by Geiss et al. [1978] and Balsiger et al. [1980] typically show the presence of O^+ (along with H^+) as a major constituent of magnetospheric hot plasma at energies below ~ 16 keV/charge. The presumption is that such ions enter the plasma sheet with several keV/charge as constituents of the auroral ion beams that are characteristic of the PM (afternoon-evening) sector [Ghielmetti et al., 1978]. The large potential drops along magnetic-field lines in the auroral oval thus enable the ionosphere to supply both O^+ and H^+ to the plasma sheet in quantities (and at energies) far in excess of those characteristic of the polar wind, which had been (~ 10 years ago) the favored medium for transfer of ionospheric plasma to the ring current and radiation belts [e.g., Axford, 1970].

The plasma sheet consists also of moderate-energy ($\lesssim$ 10-keV) ions and electrons from interplanetary space (e.g., from the solar wind) that have entered the boundary-layer convection pattern at the polar cleft or elsewhere on the magnetopause, become part of the plasma mantle, and thence been convected into the plasma sheet. Whatever their source, charged particles that populate the plasma sheet are subject to further energization by both adiabatic and non-adiabatic processes during convection and diffusion into the region of geomagnetically trapped radiation. One plasma-sheet process that seems unavoidable in this context is the "current-sheet acceleration" described recently by Lyons and Speiser [1982]. This process involves the violation of guiding-center theory in regions where the gyro-radius of a particle is not small compared to the scale length on which the magnetic field varies, and thereby enables the particle to be energized by the cross-tail electric field. The field geometry used by Lyons and Speiser [1982] was shown by Stern and Palmadesso [1975] not to allow particle energization by the cross-tail electric field if the first two adiabatic invariants were conserved.

Although the ring current is derived from the plasma sheet by magnetospheric convection and radial diffusion, the ion composition of the ring current can differ greatly from that of the plasma sheet. This is true because of the importance of charge exchange in ring-current dynamics. The loss rate due to charge exchange is much greater for H^+ ions than for O^+ ions (also much smaller for He^+ than for O^+) at energies ≤ 20 keV [Tinsley, 1976]. This means that He^+ or O^+ might dominate H^+ in the ring-current composition studies of Balsiger et al. [1980] by virtue of their greater survivability, even if the plasma sheet were predominantly H^+. The evidence on ion composition in fact seems to favor O^+ and H^+ over He^+ in this low-energy portion of the ring current, presumably because of a helium deficiency in the plasma sheet itself.

Ion-composition evidence for the main body of the ring-current spectrum ($E \sim 20$-80 keV) is necessarily less direct, since it has been difficult to fly ion-identifying spectrometers that would cover the range from ~ 20 keV/charge to ~ 100 keV/nucleon [e.g., Cornwall and Schulz, 1979]. However, Lyons and Evans [1976] were able to argue from the anomalously slow decay rate of the ring-current particle fluxes following the main phase of a magnetic storm that the major ion in the ring current could not have been H^+. In other words a hydrogen ring current would have decayed much faster than the observed ring-current ion flux did after removal of the source. The argument was not air-tight, since it ignored (a) the likely possibility that radial diffusion would continue during recovery phase and (b) the adiabatic energization that ring-current particles would experience through the electric field induced by decay of the ring current itself. However, the essential conclusion of Lyons and Evans [1976], concerning the importance of ions heavier than H^+ in the ring current, seems to have been correct.

Of course, charge exchange may not be the only loss process important for ring-current ions. Another possibility is the electromagnetic ion-cyclotron instability associated with pitch-angle anisotropy in the ion distributions [Cornwall, 1966]. In prior studies the anisotropy had been a postulated consequence of radial diffusion and pitch-angle diffusion. However, Cornwall [1977] broke with this tradition by explicitly calculating the proton anisotropy that would develop in consequence of charge exchange (since geomagnetically trapped particles experience a bounce-averaged atmospheric density that increases with mirror latitude) until instability occurred. In subsequent studies by Solomon and Pellat [1978] and by Kaye et al. [1979] a purely isotropic source at $L \sim 10$ was postulated, and the phase-space density was mapped to lower L values (and various longitudes) by means of Liouville's theorem. Pitch-angle anisotropies and discontinuities in energy spectra occurred as direct consequences of the kinematics of charged-particle motion in the presence of a dawn-dusk convection electric field. Kaye et al. [1979] in particular found that the linear growth rates calculated from their anisotropic proton distributions inside the plasmasphere on the dusk meridian showed maxima and cut-offs in good correspondence with the band-limited wave spectra observed there.

Not all of the waves in the magnetosphere have been generated by magnetospheric plasmas. The occurrence of lightning-generated whistlers is well documented, for example. Waves of anthropogenic origin include signals from ground-based radio transmitters and harmonics from power lines. In recent years interest has centered on the question of whether such man-made waves can contribute significantly to the pitch-angle diffusion and eventual precipitation of geomagnetically trapped particles. Vampola [1977] and Vampola and Kuck [1978] have discerned geographically correlated features in the precipitating electron distribution that seem to suggest a decisive role for ground-based VLF radio transmitters in the diffusion process. Park and Helliwell [1978] and Luette et al. [1979] have described the partial control of power-line harmonics over chorus emissions, and hence presumably over the electron precipitation with which chorus is known to be associated. Those arguing against the importance of anthropogenic waves for the radiation belts have included Imhof et al. [1978], Lyons and Williams [1978], and Tsurutani et al. [1979]. It could be that the advocates and opponents are not in direct conflict. The former tend to emphasize the importance of man-made wave sources in controlling the geographic longitude at which precipitation occurs, whereas the latter emphasize the importance of natural wave sources for determining the lifetimes and gross features of the pitch-angle distributions of trapped particles. Thus, there could be truth on both sides of the controversy.

Moreover, the very idea that waves of technological origin might influence the radiation belts in some observable way has provided a stimulus for theoretical study of the wave-particle interactions involved. In this context, Inan et al. [1978] have computed the change $\Delta\alpha_0$ in equatorial pitch angle that an electron would experience through an equatorial resonance with a monochromatic (single-frequency) whistler-mode wave propagating along the magnetic field. The inhomogeneity of the magnetic field limits the duration of cyclotron resonance in this case [e.g., Schulz, 1972], but at wave amplitudes $\gtrsim 3$ mγ Inan et al. [1978] found clear evidence of test particles becoming trapped in the wave-form and thus having their duration of resonance prolonged. Nonlinear phenomena of this sort can violate the first two adiabatic invariants of charged-particle motion, modify the distribution function of geomagnetically trapped particles, and (thereby) affect the stability of the magnetospheric plasma to various wave modes. For example, Cornilleau-Wehrlin and Gendrin [1979] have reported the observation of transmitter-induced quiet bands in the VLF (very-low-frequency, 3-30 kHz) noise spectrum and have interpreted this phenomenon in terms of nonlinear wave-particle interactions in the inhomogeneous $\mathbf{B}$ field.

Violation of the first two adiabatic invariants through human intervention does not imply significant violation of the third invariant by such means. Indeed, the important mechanisms for radial transport (third-invariant violation) typically require electric or magnetic disturbances of magnetosphere-wide extent, which could not likely be produced from earth within the constraints of international law. Human activity in the area of third-invariant violation has thus focused on the measurement of natural magnetospheric disturbances. In this context Lanzerotti et al. [1978] have analyzed the spectrum of (presumably) large-scale disturbances of the earth's magnetic field at synchronous altitude, using data from the ATS-6 spacecraft. By evaluating the spectral density as a function of resonant-particle drift frequency, Lanzerotti et al. [1978] were able to estimate the contribution of such magnetic disturbances to the radial-diffusion coefficients of geomagnetically trapped electrons. Holzworth and Mozer [1979] have performed a similar analysis of (presumably) electrostatic disturbances measured on simultaneous balloon flights at six auroral-zone locations spanning 180° of longitude. Theoretical considerations [e.g., Cornwall and Schulz, 1979] suggest that electrostatic impulses are the more important for transporting lower-energy particles, and that magnetic impulses are the more important for transporting higher-energy particles. Empirical studies of inner-zone proton diffusion [e.g., Croley et al., 1976] suggest that a first invariant $M \sim 100$ MeV/gauss separates high energy from low in this context, for particles of vanishing second invariant J. Thus, for example, the ring current ($M \sim 20$ MeV/gauss) is transported mainly by electrostatic disturbances.

Conversely, the radial diffusion of relativistic electrons at $L \sim 6$ occurs mainly through interaction with magnetic impulses, as Lanzerotti et al. [1978] had assumed. Moreover, an individual impulse is known to leave a characteristic signature in the azimuthal distribution of particles around their drift shell. The signature is discernible for several drift periods, depending on the energy resolution of the detector, as the electrons belonging to the outer-zone energy spectrum drift past the observer at their respective (adiabatic) drift rates. Chanteur et al. [1977, 1978] have recently studied this "drift-echo" phenomenon with great care and have confirmed its observational significance beyond any reasonable doubt.

Drift echoes in relativistic-electron channels are thus a consequence of impulsive temporal changes in the day-night asymmetry of the magnetosphere. Such configurational changes have dynamical effects on the radiation belts, effects that can be expressed by means of a radial-diffusion coefficient. However, even the static day-night asymmetry of the quiet magnetosphere has observable consequences for radiation-belt particle distributions. One such consequence is the observed tendency [e.g., West, 1979] of outer-zone electrons to show an anomalous pitch-angle anisotropy at high energies ($E \gtrsim$ 500 keV) on the night side of the magnetosphere, such that the maximum particle intensity occurs at equatorial pitch angles α_0^* and $\pi - \alpha_0^*$ different from $\pi/2$. The relative minimum in particle flux at $\alpha_0 = \pi/2$ is thus a signature of the day-night asymmetry of the magnetosphere. Recently, Baker et al. [1978] have made quantitative use of this anomalous pitch-angle anisotropy on the night side as a measure of day-night asymmetry in the underlying $\underset{\sim}{B}$-field configuration, and thus of the strength of the tail current. On this basis they have successfully used the degree of pitch-angle anisotropy (even at energies as low as 30-300 keV) to predict the occurrence of geomagnetic substorms, which might be expected to follow strong enhancements of the tail current.

The foregoing highlights illustrate the scope of radiation-belt research that has occurred during the IMS period. The selection of topics is not meant to be exhaustive by any means. The recent review by Schulz [1980] included citations of about 80 references in context and more than 400 in a supplementary bibliography, and this was supposed to cover only a two-year period (roughly September 1977 to November 1979). A thorough treatment of the entire IMS data-acquisition phase (1976-79) would not be feasible in the space available here, but a feeling for the flavor of IMS research on radiation-belt science nevertheless emerges. The remainder of the present work is devoted to an exploration of subject-areas that seem ripe for further progress in the continuing effort to understand the dynamics of the earth's radiation belts.

RADIATION-BELT EVOLUTION

Charged-particle intensities in the earth's radiation belts often fluctuate by orders of magnitude about the mean value characteristic of a given species, L value, equatorial pitch angle, and energy. Part of the fluctuation is adiabatic, being related to a general expansion or contraction of drift shells in the magnetosphere. The other part of the fluctuation is not adiabatic, being related to the transport of particles across drift shells or into the loss cone or to lower energy, for example. Non-adiabatic enhancements of particle flux are typically associated with radial diffusion, which is a common consequence of unsteady magnetospheric convection or of azimuthally asymmetric impulses in the magnetospheric $\underset{\sim}{B}$ field. Non-adiabatic decay of particle intensity is typically associated with pitch-angle diffusion, charge exchange, or energy loss.

The foregoing associations are, of course, largely schematic. It is not likely that well-known loss processes actually disappear during particle-flux enhancements, nor that radial diffusion disappears as particle fluxes decay. It is more likely that the diffusion coefficients associated with certain transport processes are modulated in time, and that the boundary condition on the particle intensity at some high L value ($L \sim 10$, but variable) likewise varies in time.

Thus, there is a reasonable prospect of modeling the dynamical evolution of the earth's radiation belts by means of a Fokker-Planck equation in which the transport coefficients vary with time, as do the boundary conditions. The kinematical entities in such a formulation are the adiabatic invariants of charged-particle motion, and these are related to observables such as energy and pitch angle by transformations that depend on the parameters of the magnetospheric model. The need to take account of adiabatic temporal variations of magnetospheric parameters while organizing particle data is widely recognized in principle but rarely honored in practice. Progress in radiation-belt theory has nevertheless advanced to the stage that the subject shows clear signs of maturity.

Recent years have seen the development of a very good steady-state understanding of radiation-belt structure over a considerable spectrum of charged-particle energies. The steady state is established in concept by balancing radial transport (mainly diffusion) against known loss processes (e.g., pitch-angle diffusion, energy loss via ionization and plasmon emission, charge exchange) and imposing reasonable boundary conditions on the phase-space density at high and low L values. The actual radiation belts are rarely in the steady state, however, and the ultimate goal of radiation-belt theory is to account for the observable variations of charged-particle intensities there by means of the Fokker-Planck equation with time-dependent transport coefficients and time-dependent boundary conditions. Thus, the notion that magnetospheric dynamical processes operate one-at-a-time, e.g., first an injection and then a decay, is largely obsolete. What really happens is that the dynamical processes continue to operate simultaneously (whether in superposition, in competition, or in cooperation) while the magnitudes of their respective transport coefficients vary (whether in correlation, in anti-correlation, or independently). The net result of all this, and of the temporal variation of source strengths and boundary conditions, is that the radiation intensity evolves over a multiplicity of time scales ranging from minutes (the drift-echo time scale) to millennia (the time scale for "secular" variation of the earth's dipole moment).

It has long been recognized that transport coefficients, source strengths, and boundary conditions could vary with time. However, the realization is now developing that such variation is not just a curiosity. Indeed, the temporal variation of transport coefficients, source strengths, and boundary conditions constitutes the essence of radiation-belt behavior during magnetic storms and radiation-belt evolution over the solar cycle.

One example of a phenomenon seemingly contingent on the solar-cycle modulation of source strength and transport (Coulomb-ionization loss in this case) is illustrated in Figure 1 [Croley et al., 1976]. The observations were made during 1969, i.e., around solar maximum. The feature of interest is the non-monotonicity of the inner-zone proton energy spectrum at low altitudes, i.e., at the larger values $X \equiv [1 - (B_0/B)]^{1/2}$, where B_0 and B are the equatorial and local magnetic-field intensities, respectively. This feature had been anticipated (see Figure 2) by Blanchard and Hess [1964] on the basis of a time-dependent solution of the Fokker-Planck equation in which the solar-cycle modulations of cosmic-ray intensity (hence of the proton source) and atmospheric density (hence Coulomb-ionization loss) were explicitly considered (note especially the spectrum predicted to occur three years after solar minimum). The ingredient notably missing from the work of Blanchard and Hess [1964] is radial diffusion, the importance of which has since been demonstrated in steady-state solutions by Farley and Walt [1971]. However, steady-state solutions (e.g., the upper dashed curve in Figure 2 corresponding to solar-minimum conditions and the lower dashed curve corresponding to solar-maximum conditions) do not satisfactorily approximate any of the time-dependent solutions (solid curves) obtained for the various phases of the solar cycle. Thus, there remains the task of obtaining time-dependent solutions of the Fokker-Planck equations, but with radial diffusion realistically included.

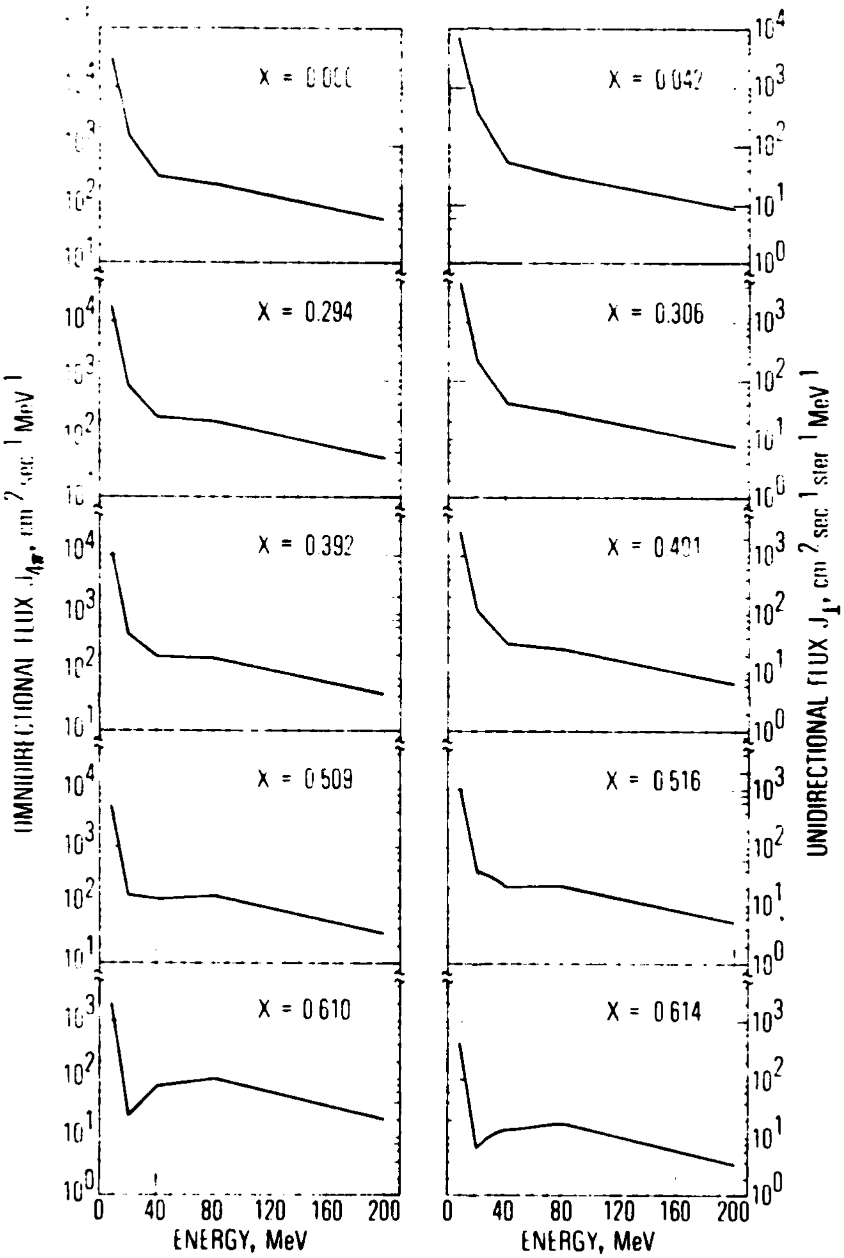

Figure 1. Inner-zone proton spectra at L = 1.475 during 1969 (near solar maximum), as unfolded from OV1-19 counting-rate data by Croley et al. [1976].

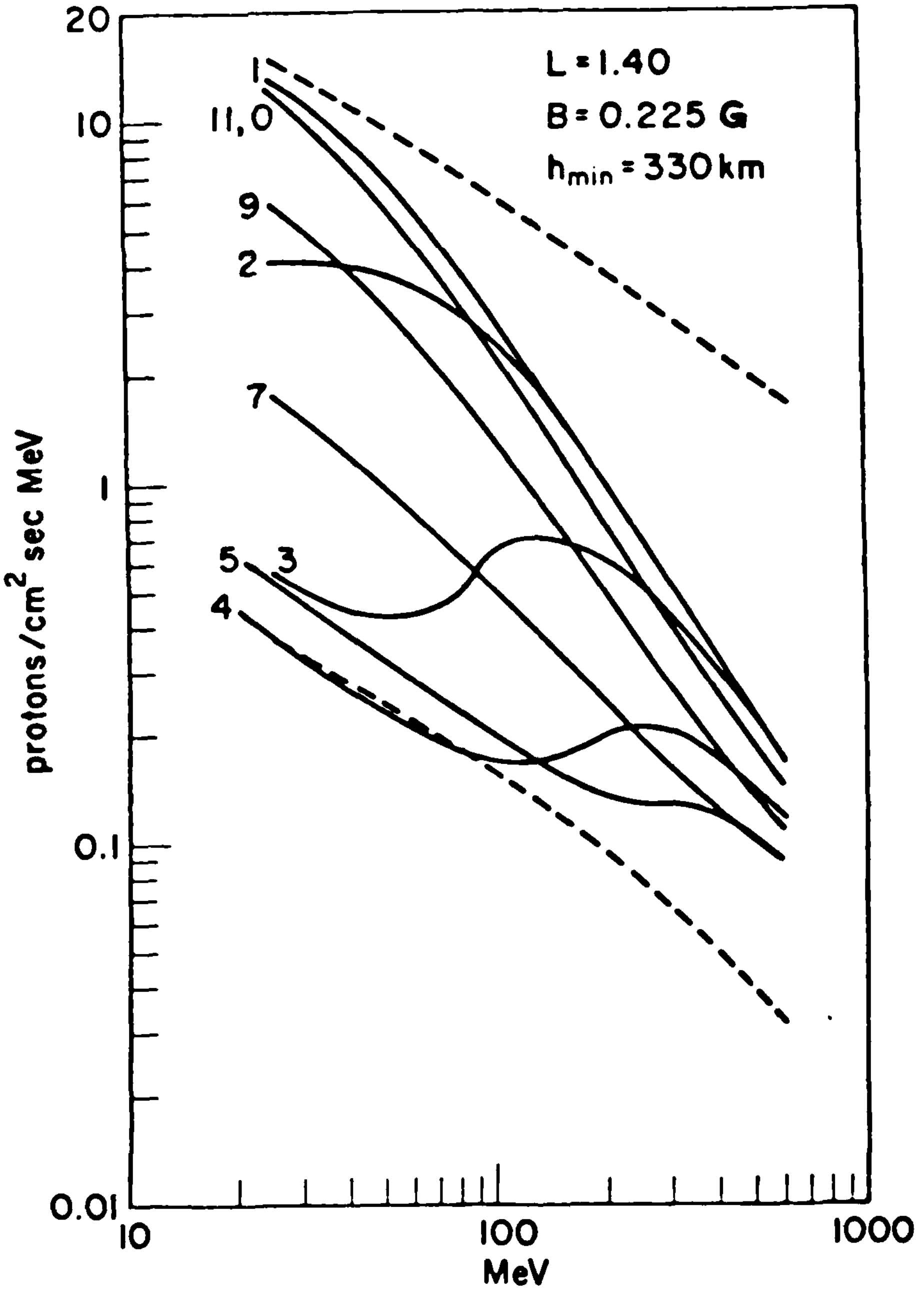

Figure 2. Inner-zone proton spectra predicted for X = 0.704 by the steady-state (dashed curves) and time-dependent (solid curves) transport models of Blanchard and Hess [1964], in which radial diffusion is neglected. Solid curves are identified by time in years from solar minimum, and perigee of the mirror-point trajectory is denoted by h_{min}.

Temporal variation of the transport coefficients likewise offers an explanation for a long-standing puzzle concerning high-energy outer-zone electrons. These frequently have a pitch-angle (α) distribution with a relative minimum (rather than an absolute maximum) at $\alpha = 90°$. It is not surprising that this can happen in the nightside magnetosphere. Pfitzer et al. [1969] have offered a purely adiabatic explanation of the nightside phenomenon, cited above in connection with the work of Baker et al. [1978], which is a consequence of the azimuthal non-degeneracy of drift shells generated by particles released with different equatorial pitch angles (α_0) on the same field line. Figure 3 [Luhmann and Schulz, 1979] illustrates the effect for ATS-1 data [Pfitzer et al., 1969] at $\alpha_0 = 90°$ and $\alpha_0 = 65°$ on the basis of a simplified mathematical description of the kinematics. It is sufficient for present purposes, however, to focus on the data points themselves and to disregard the model. It is clear that the 65° flux in the higher energy channel (i.e., at 0.5-1.0 MeV) exceeds the 90° flux not only near midnight (as one would expect) but well beyond the dusk meridian and into the dayside magnetosphere. This is a true puzzle, since nothing in the steady-state dynamics of radiation-belt electrons is known to produce negative anisotropy (i.e., a field-aligned elongation of the pitch-angle distribution) on the diurnal average.

Of course, the puzzle could be resolved by saying that the particle source provides negative anisotropy, e.g., in the form of field-aligned beams. However, this would be more plausible for ring-current ions (not shown in Figure 3) than for high-energy electrons. On the other hand, an explanation based on time-varying boundary conditions seems plausible. Just as inward radial diffusion creates positive anisotropy [Nakada et al., 1965], outward radial diffusion produces negative anisotropy. Steady-state radial

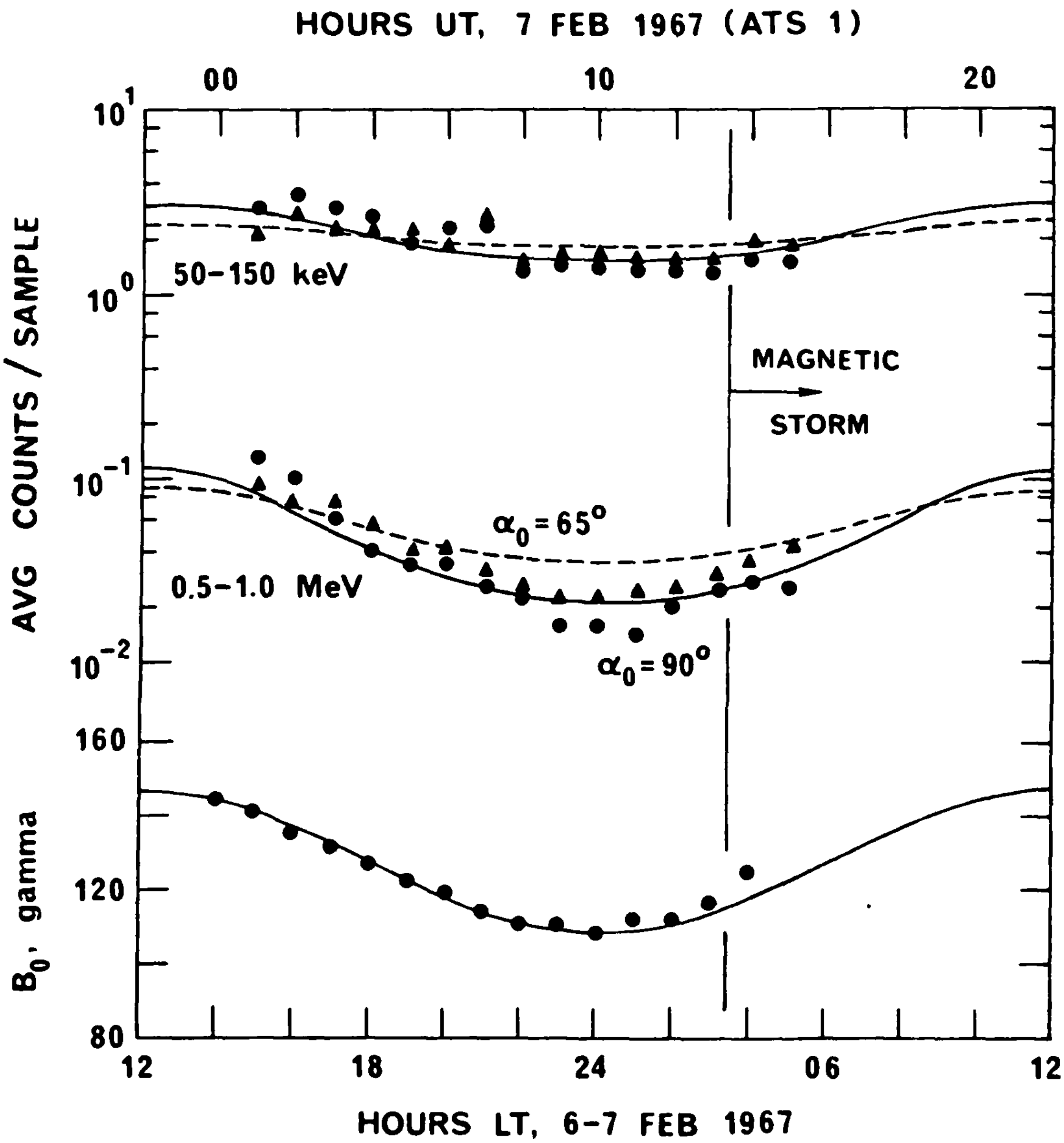

Figure 3. Comparison of ATS-1 data [Pfitzer et al., 1969] with expectations based on model of Luhmann and Schulz [1979] for 7 February 1967 (UT). Solid curves represent either direct fits (for B_0) or indirect fits (for $\alpha_0 = 90°$ via B_0) to the corresponding data (filled circles). Dashed curves (for $\alpha_0 = 65°$) represent genuine extrapolations based on drift-shell tracing, and comparison with corresponding data (filled triangles) determines the success of the model.

diffusion of outer-zone electrons typically proceeds inward (since $\partial\bar{f}/\partial L > 0$) from an outer boundary at which the azimuthally-averaged phase-space density ($\bar{f}$) at fixed M and J (adiabatic invariants) is a maximum with respect to L [e.g., Lanzerotti et al., 1970]. However, the distribution of $\bar{f}$ need not be monotonic with L if the state of the radiation belt is not steady. For example, a sudden diminution of the boundary value of $\bar{f}$ would initiate a temporary condition of outward radial diffusion in the outer portion of the outer zone. If the positive anisotropy associated with the prior condition of inward radial diffusion had meanwhile been reduced or obliterated by pitch-angle diffusion, the net result of the above sequence of events might well be the appearance of negative anisotropy in the outer portion of the outer zone, even on the diurnal average. However, this would happen only during periods of diminished boundary values of $\bar{f}$, i.e., perhaps during magnetically quiet periods or when the earth's magnetosphere is not connected to Jupiter's along the spiral of the interplanetary magnetic field.

This last remark about Jupiter is not entirely "off the wall." Jupiter's magnetosphere is known [Teegarden et al., 1974; Chenette et al., 1974, 1975] to be a source of relativistic ($E \sim 1$-6 MeV) electrons for interplanetary space, even at 1 AU. A careful analysis of data from terrestrial satellites [Krimigis et al., 1975; Mewaldt et al., 1976] reveals a 13-month quasi-periodicity in the monthly-averaged interplanetary flux of such electrons, with the broad maximum centered on those months during which Jupiter and the earth were most probably connected by an interplanetary field line, as determined by the mean solar-wind velocity. Since the actual solar-wind velocity at 1 AU varies with time, enhancements of the interplanetary electron flux ($E \sim 1$-6 MeV) are necessarily sporadic, but a sliding time-average reveals the 13-month recurrence quite nicely. Baker et al. [1979] made the sensible suggestion (cited above) that such Jovian electrons contribute to the earth's radiation belts, for which the interplanetary particle flux constitutes the outer boundary condition in L.

SOURCE OF RING CURRENT

The outer boundary condition for the ring current is the plasma sheet. Specification of the boundary condition might be achieved by assigning a temperature and partial density to each plasma-sheet constituent, or preferably by describing the entire energy spectrum for each constituent. The boundary between the plasma sheet and the ring current is, according to this viewpoint, the boundary between open and closed drift shells of the constituent particles. Thus, the boundary is not a unique location in space, e.g., a boundary at L = 10 in the idealized model of Kaye et al. [1979], but its L value is instead a function of particle energy, charge, equatorial pitch angle, and local time. Temporal variation of the magnetospheric $\underset{\sim}{E}$ or $\underset{\sim}{B}$ field transports particle trajectories across this conceptual boundary as if by diffusion. However, owing to the complexity of the trajectories and of the boundary itself, the diffusive description is more difficult to formulate here than in the radiation belts.

Lyons and Williams [1980] have argued that the source of the storm-time ring current is the quiet-time ring current. In support of this argument they have shown that the phase-space density of particles in the storm-time ring current matches that of particles in the quiet-time ring current over a broad spectrum of M and J (adiabatic invariants) if one considers the distribution to have been "transported" appropriately across L. The physical origin of such "transport" is problematical, but presumably related to unsteady magnetospheric convection. Transport by induced electric fields is probably unimportant because it seems to have the wrong sign, i.e., an inward transport of particles corresponding to an outward displacement of field lines.

Although Lyons and Williams [1980] hesitate to characterize it as such, the "transport" of particles seems to be quasi-diffusive. An individual particle is displaced either inward or outward in L, depending on its position in longitude at the time of maximum convection electric field. However, the radial gradient of phase-space density (f) is outward at fixed M and J, and so the "diffusion" current would be inward. This interpretation holds qualitatively even for a single impulse in the convection electric field, although the mathematical description is not rigorously diffusive in this case.

Enhancement of the diffusion coefficient in the presence of charge exchange tends to reduce the gradient of drift-averaged phase-space density ($\bar{f}$) with respect to L, even if the outer boundary condition on $\bar{f}$ remains unchanged. The reduced gradient might make it appear that $\bar{f}$ had been "mapped" from higher L values to lower, as Lyons and Williams [1980] have argued, but the quantity to which Liouville's theorem properly applies is f and not $\bar{f}$. Drift-phase mixing among particles of different energy within the detector bandwidth makes f itself difficult to observe and suppresses drift-periodic echoes (see above) in the particle flux. Irregularities in the acknowledged temporal variation of the convection electric field may likewise tend to mask drift echoes. The extent to which pre-storm phase-space densities at higher L values seem to match storm-time phase-space densities at lower L values is quite remarkable, but it would be highly instructive to develop a model of the electric impulse that "transports" the energetic particles in the manner inferred from this comparison.

It is widely held that radial diffusion occurs only on time scales large compared to the mean interval between randomly spaced impulses in the magnetospheric $\mathbf{E}$ or $\mathbf{B}$ field. While this widely held belief is formally correct, it overlooks the similarity of consequence between the diffusive description and the response of particle distributions to a single impulse. It should be easy enough to demonstrate this similarity. The first step would be to calculate explicitly the response of a particle to an impulse in the convection electric field, i.e., the ultimate displacement in L as a function of the particle's initial longitude or local time (C. E. McIlwain, personal communication, 1981). The result would yield a "Green's function" for the final distribution of particles in L, as derived from their initial (pre-impulse) distribution in L. This "Green's function" should be compared with the Green's function that satisfies the radial-diffusion equation, in which the diffusion coefficient might well be modeled as being proportional to a Dirac delta-function in time. The two Green's functions thus constructed will not have quite the same functional form, if only because the former is bounded in L while the latter is not. However, the two should turn out to have about the same width (e.g., at half-maximum) in L, and it is in this sense that even a single impulse can be said to produce radial diffusion, or at least to have consequences that are difficult to distinguish from radial diffusion.

Figure 4 illustrates the now-classic results of Nakada et al. [1965], results that have seemed to imply the sufficiency of radial diffusion at fixed M and J as a means of energizing outer-zone protons in the magnetosphere. The solid curves were constructed by measuring the *e*-folding energies E_0 of exponential proton spectra at equatorial pitch angles appropriate to a mapping of α_0 = 10°, 20°, 30°, and 90° from L = 7 at fixed M and J. The dashed curves show the corresponding energy variation of an individual proton with L, but are positioned on the logarithmic ordinate so as to best fit the observed variation of E_0 with L. The dashed curves seem to converge on a common (isotropic) value of $E_0 \sim 12$ keV at $L \sim 10$. It is natural, therefore, to associate the parameters $E_0 \sim 12$ keV and $L \sim 10$ with the boundary condition on

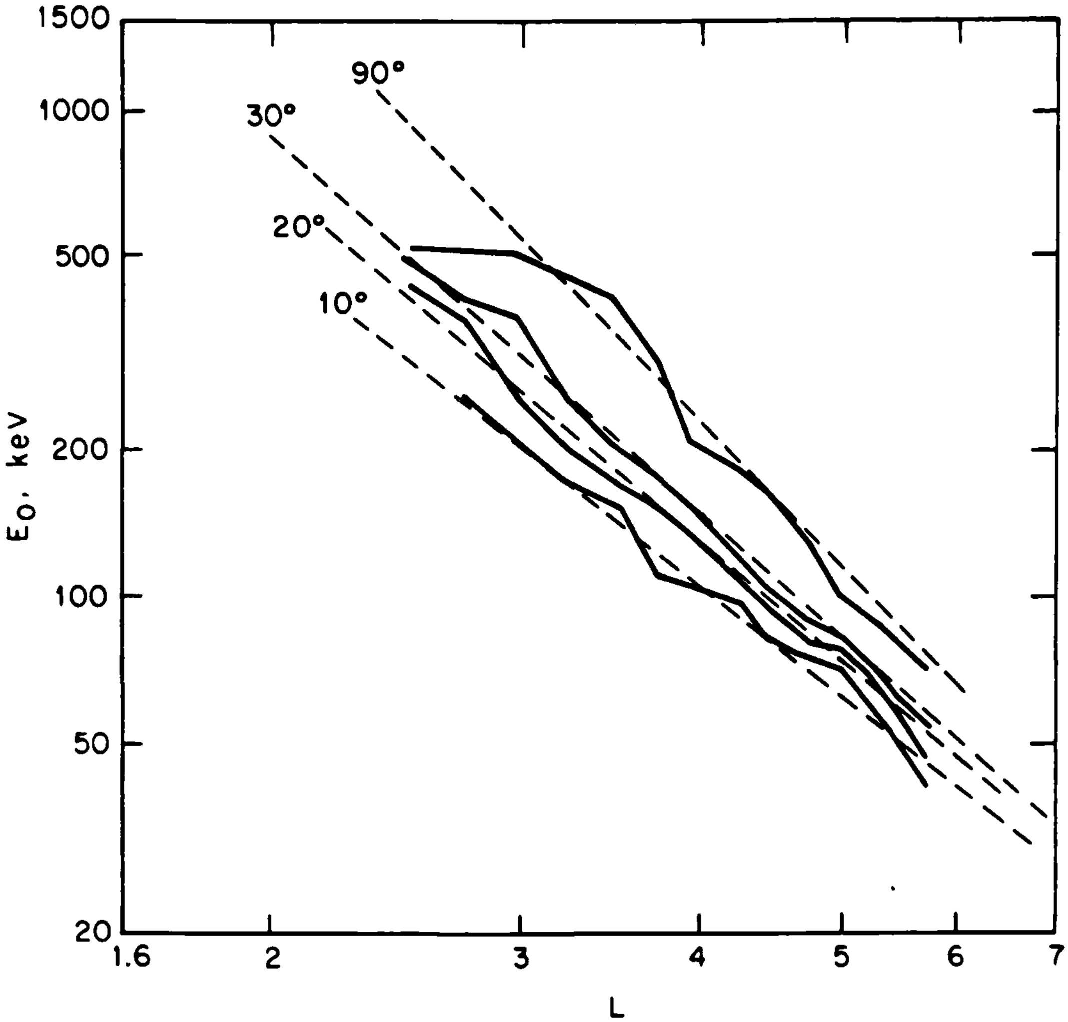

Figure 4. Empirical e-folding energies (solid curves) of Davis-Williamson proton spectra at equatorial pitch angles appropriate to mappings of indicated values of α_0 from L = 7 at fixed M and J (adiabatic invariants); dashed curves show the corresponding energy variations of individual protons with L [Nakada et al., 1965].

the ring current, i.e., with the plasma sheet itself.

However, this association seems objectionable (S. M. Krimigis, personal communication, 1981) in the light of present knowledge concerning the plasma sheet. Quite frankly, it is difficult to assign the plasma sheet a proton temperature $\gtrsim 6$ keV in good conscience. This certainly does not mean that the radiation-belt ideas of Nakada et al. [1965] are wrong in any sense of the word, but it does mean that a more sophisticated concept of the plasma sheet would be in order. For example, the plasma sheet need not be regarded as a purely homogeneous medium. Perhaps the tailward portion is quasi-homogeneous, with a proton temperature ~ 6 keV maintained by violation of the first adiabatic invariant [e.g., Lyons and Speiser, 1982] in the presence of the usual cross-tail electric field, while the earthward portion is further energized adiabatically by the inevitable component of gradient-curvature drift in the direction of the same convection electric field. Perhaps it is significant that the boundary between open and closed drift shells occurs farther out in the magnetosphere for particles of higher energy. This consequence of the convection electric field would allow the higher-energy plasma-sheet particles to be energized by a larger factor through radial diffusion than the lower-energy particles (a geophysical analogy of the rich becoming richer). Perhaps instead some special population of particles, having been energized by mechanisms not previously contemplated, contributes significantly to the ring-current boundary spectrum. This last possibility seems the least appealing, but it cannot yet be ruled out.

ION COMPOSITION

In more innocent times it was believed that the ion composition of the ring current and radiation belts at a specified energy/nucleon should be the same as the ion composition of the solar wind. The idea was that traversal of the bow shock would separately thermalize each ionic constituent of the solar wind so as to produce a Maxwellian distribution having a temperature ~ 1 keV/nucleon as an outer boundary condition on the phase-space density, and that the diffusion equation would impose a common profile (defined by the requirement of a divergence-free radial-diffusion current) on all the constituents in the ring current and radiation belts. This concept failed to be supported by the observational data and so is considered obsolete.

One difficulty with the above concept is that the _e_-folding energy provided by thermalizing the solar wind is too small by an order of magnitude (see Figure 4, above) for assignment to a boundary at L ~ 10. Another difficulty is the neglect of ionospheric ions, which can enter the magnetosphere with several keV of energy by virtue of the field-aligned potential drop characteristic of auroral arcs in the afternoon and evening sectors. It seems, however, that entry into the radiation belt or ring current is not direct in either case, but rather occurs via the plasma sheet. Processes in the plasma sheet may enable the cross-tail electric field to heat the various ionic species further, but not necessarily by the same amount or by the same amount per nucleon. Moreover, entry of solar wind ions into the plasma sheet is modulated in part by reconnection efficiency, i.e., by the ratio of cross-tail electric field to asymptotic interplanetary electric field. The reconnection efficiency can vary considerably with time, as can the solar-wind velocity and ion-composition. Likewise, the field-aligned auroral potential drop can vary considerably with time. These are some of the uncertainties that affect the outer boundary condition for the problem of magnetospheric ion composition as a function of energy/nucleon.

Radial transport of magnetospheric ions at ring-current energies ($E \sim 10$-100 keV) is achieved primarily by unsteady electrostatic convection. The corresponding diffusion coefficient is independent of charge and mass among particles having drift periods $\gg 20$ min, the postulated decay time of an impulse in the convection electric field. However, the diffusion current is not divergence-free, since distributed losses constitute an essential ingredient of ring-current dynamics. Erosion of the ring current occurs primarily through charge exchange and perhaps through wave-particle interactions. Charge exchange favors the survival of O^+ and He^+ over H^+ and He^{++} at energies $\lesssim 50$ keV, but account must be taken of population disparities in the plasma sheet and of time scales associated with radial diffusion therefrom. Thus, it is possible for H^+ to predominate over O^+ and He^+ in the early stages of ring-current formation but not necessarily in the later stages of a magnetic storm.

Collisional processes are less important at radiation-belt energies ($E \gtrsim 200$ keV), and the mapping of ion distributions from the outer boundary to low L values can be understood in terms of a common diffusion profile with M and J (first two adiabatic invariants) conserved. One consequence of this is illustrated in Figure 5 [Blake et al., 1973]. The proton anisotropy at $L = 1.85$ is an increasing function of energy, as expected from the arguments of Nakada et al. [1965]. The alpha-particle anisotropy is larger, although its energy dependence is ambiguous in this case. The larger alpha-particle anisotropy at fixed energy/nucleon can be understood in terms of an alpha-particle temperature that is less than four times the proton temperature at the outer boundary of trapped radiation.

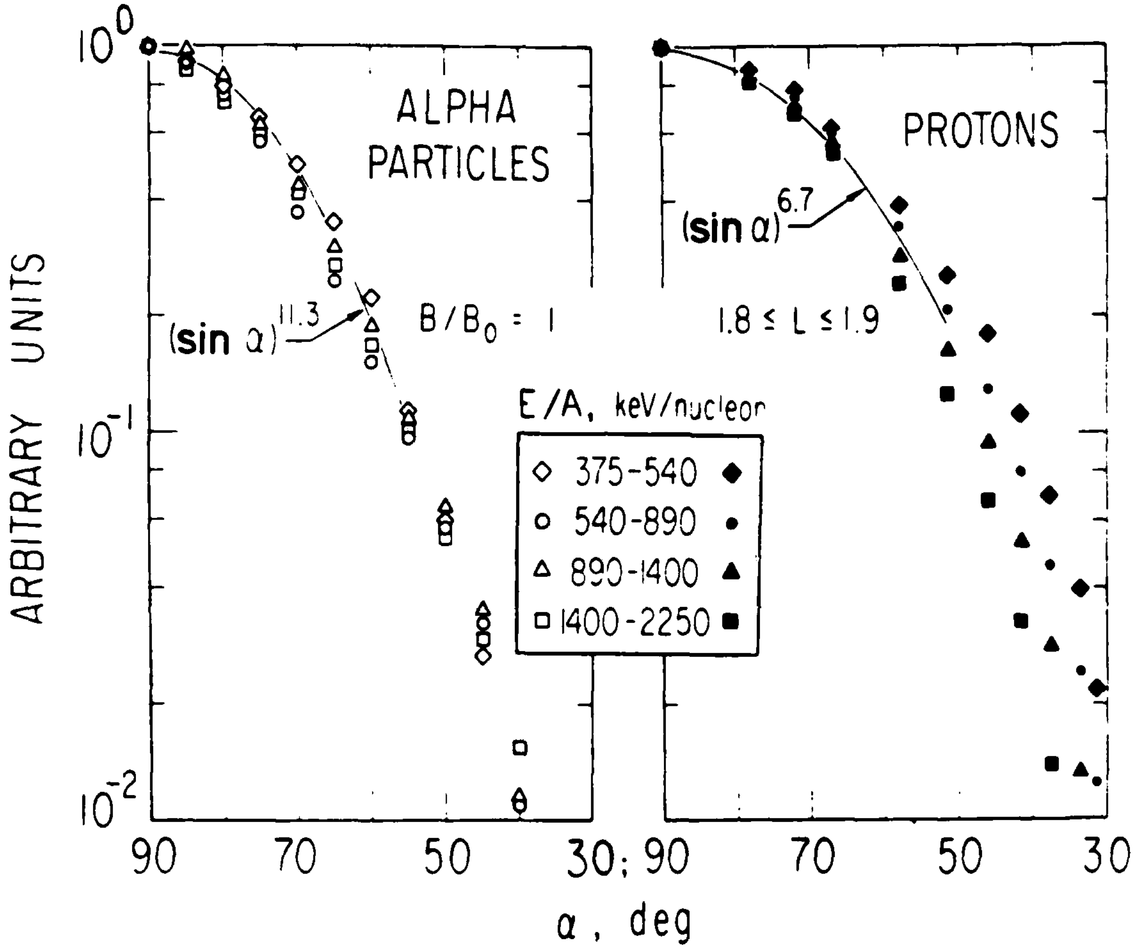

Figure 5. Equatorial pitch-angle distributions of alpha particles (including both He^+ and He^{++}, left panel) and protons (right panel) in the same four energy/nucleon passbands, as observed on spacecraft OV1-19 [Blake et al., 1973].

Much of the research emphasis on ion composition in recent years has focused on energies ≤ 20 keV, i.e., on energies so low that they are not truly in the radiation-belt range. Indeed, such energies are so low that they hardly include a significant portion of even the ring-current spectrum. It is therefore quite important to avoid sweeping generalizations in the interpretation of ion-composition results. Meanwhile, progress [e.g., Gloeckler, 1977] is being made toward the construction of ion-identifying spectrometers that operate in what had been the energy "gap" between ~ 20 keV/charge and ~ 100 keV/nucleon, as required for proper scrutiny of the ring-current spectrum.

Another advancement in space instrumentation of the past few years is that which has provided high-resolution measurements of phase-space density (f) in all three dimensions of ion-velocity space. These measurements have been of great benefit to magnetospheric research since the launching of the ISEE and GEOS spacecraft several years ago. One important application has been remote sensing of the magnetopause. Three-dimensional velocity distributions reveal proximity of the spacecraft to the magnetopause because the magnetopause tends to truncate the phase-space density distribution corresponding to particle trajectories that intersect it. Thus, the gyroradius corresponding to an observed truncation in velocity space measures the distance to the magnetopause in the plane normal to the magnetic field. This measurement has been used for monitoring the magnetopause position, orientation, and velocity as functions of time [Williams, 1979]. Another application of high-resolution ion-velocity measurements in three dimensions is the timing of ion-injection events that originate in the distant tail [Williams, 1981]. Of particular interest in this context are the ion beams that seem to travel along the magnetic field near the edge of the plasma sheet, mirror at low altitude, and travel back out along the magnetic field toward the tail. The dispersion in arrival times for different energies and pitch angles reveals the structure of the magnetic field both earthward and tailward of the spacecraft and also indicates the distance between the spacecraft and the location of the impulsive particle source. Williams [1981] found no evidence that such beams were ever scattered or otherwise impeded in their round trip from the tail to the polar cap and back. Additional applications of high-resolution velocity-space coverage in three dimensions are undoubtedly waiting to be discovered.

SUMMARY AND OUTLOOK

The purpose of this review has been to provide background material on broad topics of relevance to the data-analysis phase of IMS. The focus is balanced somewhat equally between progress achieved and progress desired. The scope of the review includes the radiation belts and the ring current. The number of references has been held down by the decision to emphasize broad principles over special topics. Recent reviews of a more exhaustive character on ion composition [Cornwall and Schulz, 1979] and energetic-particle populations [Schulz, 1980], however, have provided extensive reference lists relevant to the various general and special topics.

Looking to the future, we should of course continue (as during the data-acquisition phase of IMS) to monitor particle intensities and wave spectra with maximum possible resolution. However, the main uncertainties in radiation-belt science seem to reside beyond the radiation belts themselves. These include (1) the problem of particle energization in the plasma sheet, which defines an outer boundary condition for the ring current and radiation belts; (2) the problem of particle energization in solar flares and in Jupiter's magnetosphere, both of which seem to constitute sources for the earth's radiation belts; and (3) the relationship of large scale electric- and magnetic-field fluctuations across the magnetosphere to interplanetary parameters and geomagnetic indices that vary with time. We need not regret the impression that the major problems in radiation-belt science are not intrinsic to the radiation belts themselves. This is both a tribute to the pioneers of our field and a challenge for us to unite radiation-belt science with the mainstream of magnetospheric research, thereby to produce a comprehensive understanding of plasma processes in the solar system and their observable consequences.

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