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Energetic-Particle Populations and Cosmic-Ray Entry

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17 March 1981

Interim Report

Prepared for

SPACE DIVISION
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Los Angeles Air Force Station
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This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NITS). At NITS it will be available to the general public, including foreign nations.

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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This report constitutes a review of recent progress in the study of charged-particle access, transport, and loss with respect to the earth's magnetosphere. A major objective of studying particle access is to identify the sources of trapped and quasi-trapped radiation. Important progress in this area involves the measurement of comparative ionic abundances in the radiation belts. The historic problem of accounting for cosmic-ray cut-off latitudes as a function of particle energy is being solved by the adoption of increasingly

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realistic and accurate models of the magnetospheric B field. Progress in the estimation of particle-transport coefficients (mainly diffusion coefficients) involves the measurement of fluctuating electric and magnetic fields on the ground, at balloon altitudes, and in space. The importance of particle interactions with discrete waveforms (as distinguished from broad-banded spectral noise) is increasingly being recognized. For example, the unsteady magnetospheric convection associated with substorms contributes importantly to radial diffusion, whereas cyclotron resonance with chorus elements and other discrete excitations may contribute importantly to pitch-angle diffusion and (thus) to the loss of energetic particles from the magnetosphere. The role of man-made signals such as radio transmissions and power-line harmonics in this latter process remains uncertain and continues to be debated.

PREFACE

This report is based on a reporter-review (that of IAGA Subdivision III-4) that was presented 5 December 1979 at the XVII General Assembly of the International Union of Geodesy and Geophysics (IUGG) in Canberra, Australia. The author is pleased to thank Dr. C.-G. Fälthammar (chairman of IAGA Division III) and Dr. L. J. Lanzerotti (the elected reporter-reviewer for Topic III-4) for the invitation to present this review. He is also pleased to thank Dr. G. Rostoker and Dr. A. Nishida for suggesting that the written report be published in this journal. The author is pleased to thank the American Geophysical Union for partially subsidizing the trip to Australia under a group travel grant from the U. S. National Science Foundation. Finally, it is a pleasure to thank Inge Scanlan and Lilia Francewar for typing the final manuscript and supplementary bibliography.

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INTRODUCTION

The purpose of this work is to review recent theoretical and observational developments in the study of energetic charged-particle populations in the earth's magnetosphere. More specifically, the intended focus of this review is on developments that have occurred since the Third General Scientific Assembly of IAGA, held in Seattle toward the end of August 1977. This is not the sort of review in which the author seeks to identify the major problems that have been solved during the past few years and to specify the outstanding new problems that have emerged during the same period and now require solution. Progress in magnetospheric physics does not occur in accordance with such a stereotype. It seems instead that the basic questions addressed by magnetospheric physicists remain the same from decade to decade. What evolves over the years is the sophistication with which the basic questions are formulated, and also the detail in which answers are sought. This situation is a profound tribute to the pioneers of space research for their ability to identify the outstanding problems of magnetospheric physics at an early date. The evolving standard of sophistication with which answers to these basic questions are sought and delivered is a continuing tribute to the space-physics community as a whole.

The basic questions addressed in radiation-belt physics involve the access, transport, and loss of the charged particles with respect to the earth's magnetosphere. The question of access includes the problem of identifying particle sources. The question of transport includes the problem of identifying both diffusive and non-diffusive mechanisms by which one or more of the adiabatic invariants of a charged particle can change value. The question of particle loss includes the problem of identifying the mechanisms of pitch-angle diffusion, the size of the loss cone, the rate of energy degradation by various processes, and the lifetime against charge exchange. It is clear from this description that the questions of particle access, transport, and loss overlap somewhat in scope. There is no harm in this, since the objective of radiation-belt physics is to provide a coherent, comprehensive, and quantitative description of the energetic particle populations in the earth's magnetosphere. However, the allocation of certain topics to the "access" and "loss" categories (rather than to "transport") in the present work is necessarily arbitrary in some cases.

ENERGETIC-PARTICLE ACCESS TO THE MAGNETOSPHERE

It has long been realized that a measurement of comparative ionic abundances in the magnetosphere carries implications concerning the source of the particles observed. The basic concept is that various conceivable sources for geomagnetically trapped radiation have different ionic-abundance ratios, and that a ratio at the source should be reflected in the magnetospheric abundance ratio under certain conditions. The situation is somewhat complicated by the possibility of differences in transport rates within the magnetosphere, but there is considerable truth in the basic concept. Cornwall and Schulz (1979) have recently reviewed this concept and its limitations, together with some of the early observations of the He/H ionic abundance ratios in the magnetosphere and the puzzles that these observations presented. Spjeldvik (1979) has recently reviewed the subject from a more theoretical viewpoint, with emphasis on comparative charge-state abundances of heavier ions such as oxygen. Prangé (1978), Johnson (1979), Shelley (1979), and Hultqvist (1979) have reviewed past observations of energetic ions at altitudes $\lesssim 10^4$ km in the auroral regions and have thus emphasized ions of ionospheric origin. Young (1979) has provided a review of these, as well as more recent observations, and has thus approached the subject from a magnetospheric perspective.

Perhaps the major observational development in this area of magnetospheric research in recent years has been the placement of the ISEE and GEOS spacecraft in near-equatorial orbits that extend to high L values. Preliminary results from the instruments onboard GEOS-1, ISEE-1, and ISEE-2 appeared in six special issues of <u>Space Science Reviews</u> during 1978-79. GEOS-2 and ISEE-3 were launched following the Thirteenth ESLAB Symposium (held 5-7 June 1978 at Innsbruck, Austria), at which the preliminary results from the three earlier spacecraft were first publicly presented. The major results on ionic composition were the GEOS results of Geiss et al. (1978). Some of these are illustrated in Figures 1-2. The reader will note that the energies represented here are quite low by radiation-belt standards, and even exclude a major part of the ring-current spectrum. This difficulty arises from an instrument gap that so far has precluded observations from ~ 20 keV/charge to ~ 100 keV/nucleon (e.g., Cornwall and Schulz, 1979). However, the observations of Geiss et al. (1978) at least suggest that oxygen (O^+) is an important constituent of the ring current, along with H^+ and (to a lesser extent) helium. These results confirm the observations that Johnson et al. (1977) had made on S3-3 at locations far from the magnetic equator.

It is presumed that energetic ions enter the magnetosphere either by crossing the magnetopause or by following the electric field of an auroral arc. In support of the latter process, Ghielmetti et al. (1978) have reported the common occurrence of upward flowing energetic ions (both H^+ and O^+) of ionospheric origin, especially in the afternoon and evening sectors (see Figure 3). The local-time signature of this phenomenon is consistent with the idea (e.g., Lyons, 1980) that auroral electric fields are generated by an inherent "discontinuity" in the magnetospheric convection field. As is illustrated in Figure 4 (Swift et al., 1976), the parallel (to $\mathbf{B}$) component of $\mathbf{E}$ tends to point upward (downward) at places where the normal (to $\mathbf{B}$) component of $\mathbf{E}$ points toward (away from) the auroral arc. In the case of a dawn-to-dusk electric field, the parallel (to $\mathbf{B}$) component of $\mathbf{E}$ must therefore point upward in the PM sector and downward in the AM sector, as the results shown in Figure 3 suggest.

The signature of an auroral electric field with a strong upward component parallel to $\mathbf{B}$ is evident in the high-resolution velocity-space distributions of ions and electrons compiled by Croley et al. (1978). The results, presented in the form of contour plots on

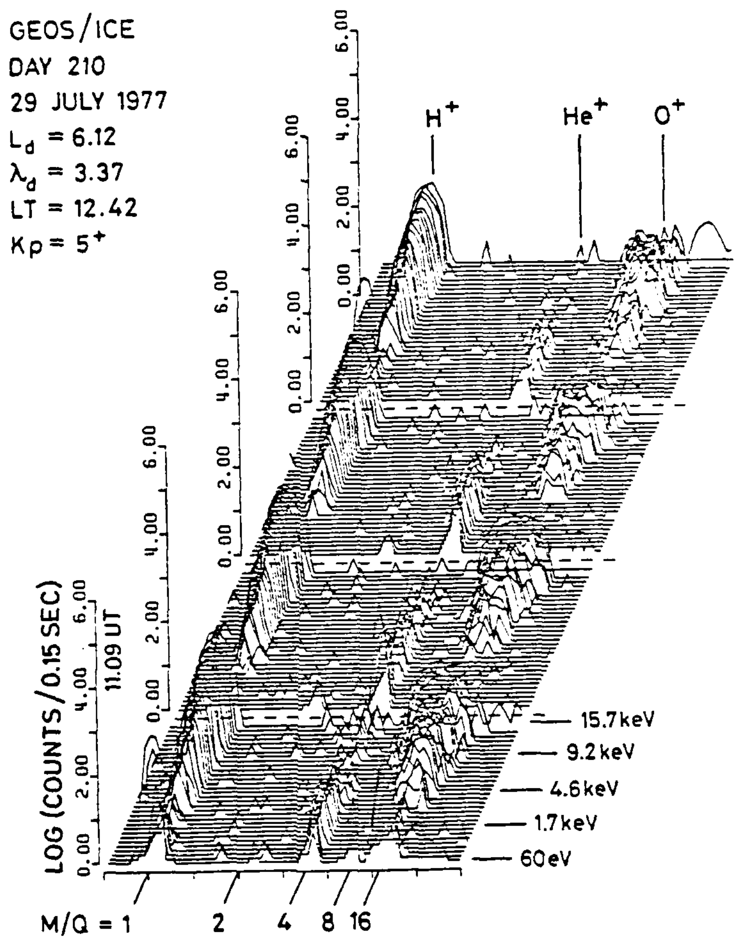

Figure 1. Three-dimensional "L-mode" mass spectra taken near noon on 29 July 1977. This was during the main phase of a magnetic storm for which D_{st} reached -100 γ (at 0700 UT). Abscissa = mass/charge; ordinate = differential flux per unit charge (Geiss et al., 1978).

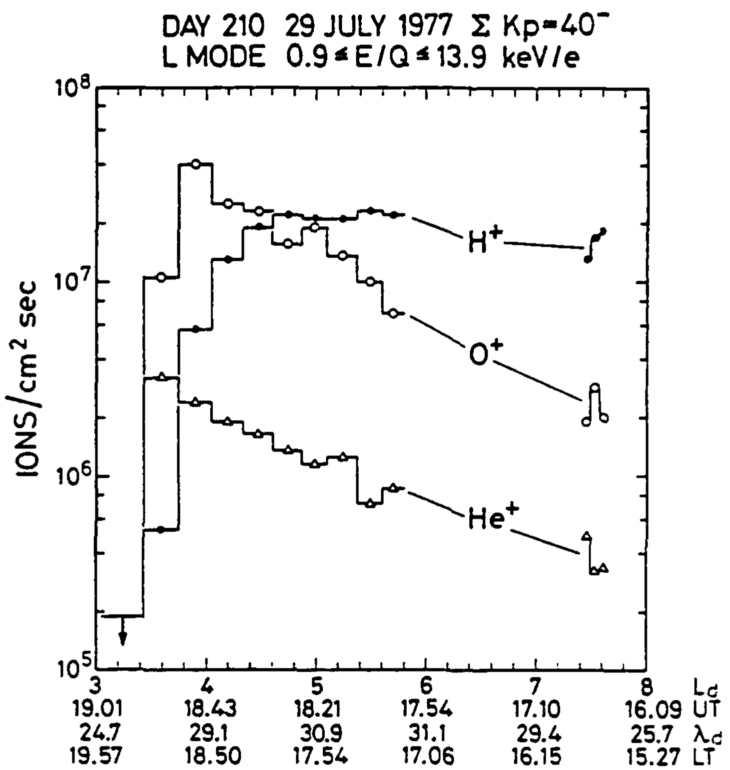

Figure 2. Radial profile of plasma composition (0.9-13.9 keV/charge) during magnetic storm of 29 July 1977 (Geiss et al., 1978).

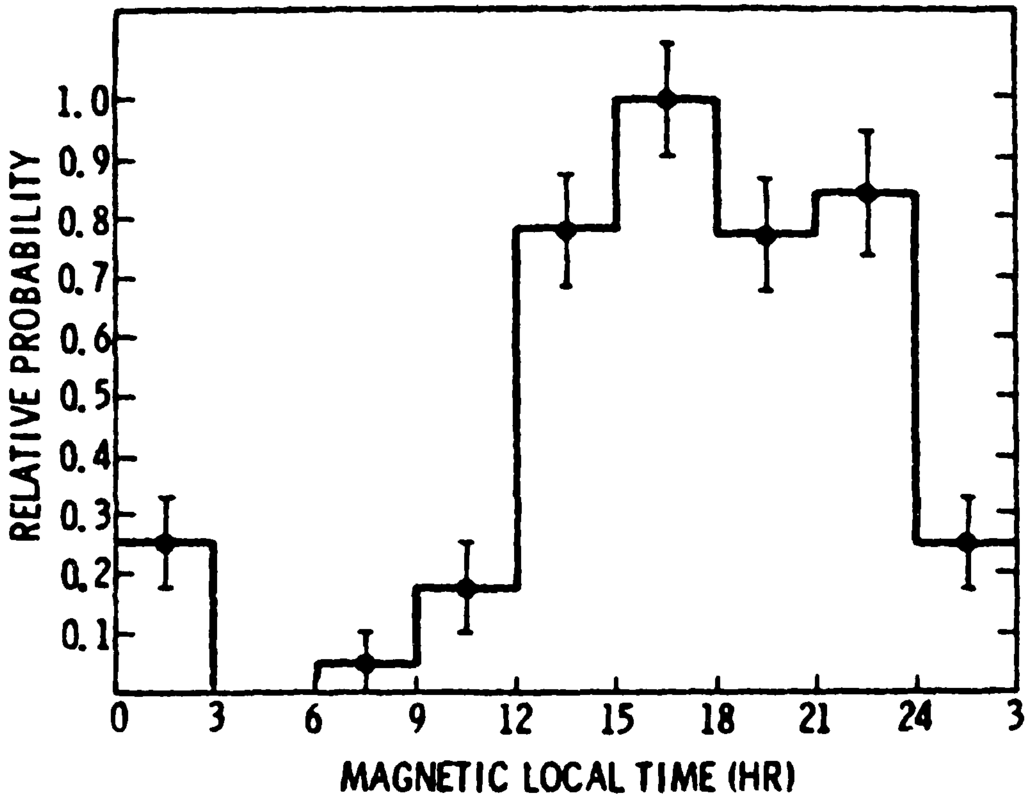

Figure 3. Relative probability-of-occurrence of an upward-flowing ion beam as a function of magnetic local time in the altitude range 6000-8000 km, normalized to 1.0 for the interval 15-18 hr MLT (Ghielmetti et al., 1978).

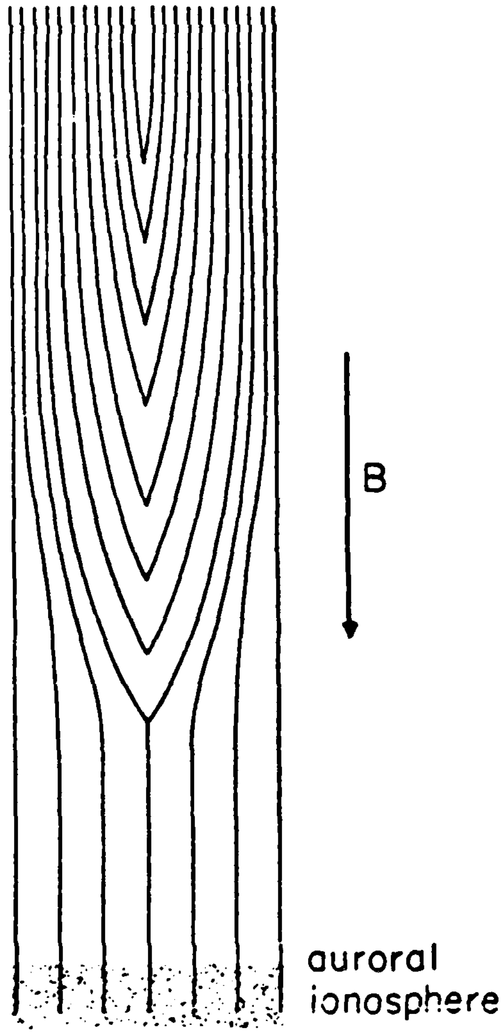

Figure 4. Schematic illustration of electrostatic equipotentials in and near an auroral arc (Swift et al., 1976). Since E is perpendicular to the equipotential surfaces, an upward E at the center of the arc corresponds to a magnetospheric E that points toward the arc from both sides.

the ($v_\parallel$, $v_\perp$) plane, reveal clearly the boundaries in velocity space that separate adiabatically distinct classes of particles constrained to move along the same field line. This is illustrated for electrons in Figure 5. Data are shown from nearly a full spin of the spacecraft (S3-3) as a precaution against aliasing; to the extent that the distributions in the upper and lower half-planes agree, the distribution thus determined is presumably a good (i.e., instantaneous) one. Torbert and Mozer (1978) observed strong localized electric fields from the same spacecraft in association with particle signatures (Mizera and Fennell, 1977; 1978) of this type.

For ions and electrons that originate not in the ionosphere but in interplanetary space, the mode of access involves crossing the magnetopause somewhere. For particles of moderate energy (≤ 10 keV) this can be a very complicated process indeed. Such particles might enter the boundary-layer convection pattern at the polar cleft or elsewhere on the magnetopause, become part of the plasma mantle, and thence be convected into the plasma sheet. Once in the plasma sheet, such particles might well be energized by both adiabatic and non-adiabatic processes during convection and diffusion into the region of geomagnetically trapped radiation.

Particle access through the magnetopause at substantially higher energies is facilitated by intrinsic violation of the first adiabatic invariant. This occurs wherever the scale size of inhomogeneities in $\mathbf{B}$ is smaller than the gyro-radius of the particle. While the magnetopause itself represents such an inhomogeneity (of ideally vanishing scale size), the probability that the magnetosphere will actually trap an incident particle can be enhanced by the additional presence of interior inhomogeneities in $\mathbf{B}$. This is illustrated in Figure 6, in which particle trajectories (as projected onto the equatorial plane of a model $\mathbf{B}$ field) are modified by encounters with a field-aligned wedge of drastically reduced $|\mathbf{B}|$. The work illustrated is that of Blake and Friesen (1979). The presence of such diamagnetic "blobs" in the magnetosphere could scatter an incident

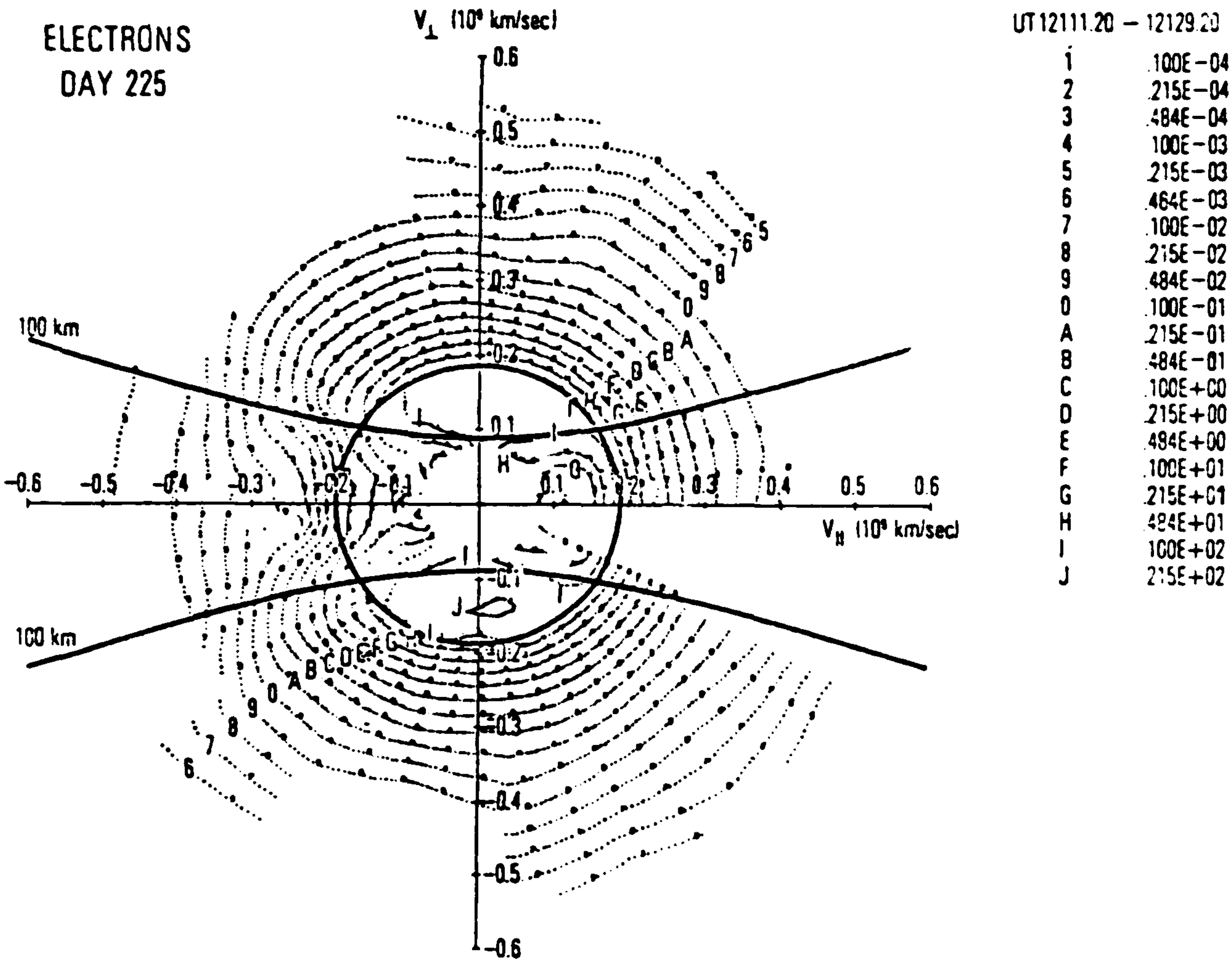

Figure 5. Contours of constant phase-space density for auroral electrons. 12 August 1976 (UT = 12120.2±9.0 sec), as determined by Croley <u>et al.</u> (1978). Hyperbola and ellipse demarcate regions of velocity space adiabatically accessible to the foot of the field line (100-km altitude) and the equator, respectively, in the presence of the parallel (to $\underset{\sim}{B}$) electric field that has been inferred from the S3-3 data for this time interval.

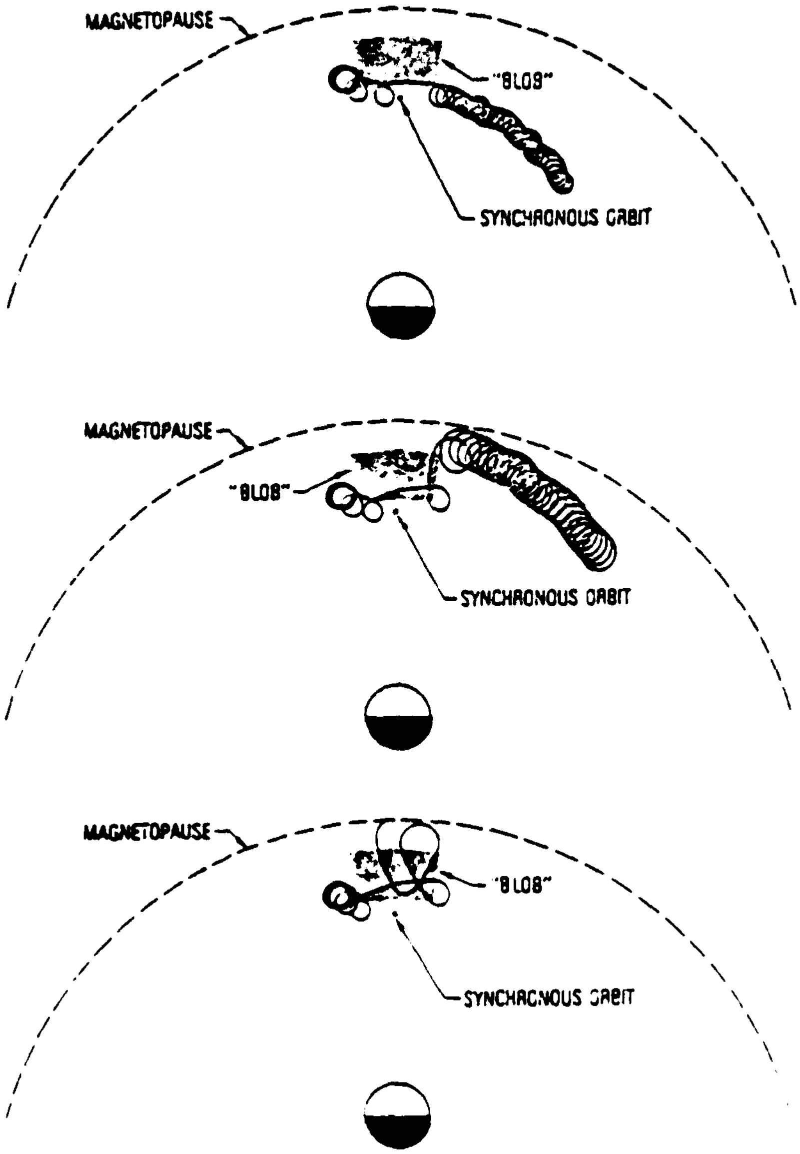

Figure 6. Representative trajectories of a 5-MeV proton, as computed by Blake and Friesen (1979) and projected onto the equatorial plane of a model $\underset{\sim}{B}$ field. The shaded region corresponds to a diamagnetic wedge in which the magnitude of $\underset{\sim}{B}$ has been reduced by a factor of ten.

particle's guiding center either toward or away from the magnetopause with roughly equal probability. However, since the source of "cosmic" rays is external to the magnetosphere, the net effect of such scattering is to facilitate particle access on the average. Many of the incident "cosmic" rays are likely to be relativistic electrons emitted from Jupiter's magnetosphere (Baker et al., 1979).

Traditional computations of cosmic-ray cutoffs necessarily omit unpredictable features such as diamagnetic "blobs" from the field model. However, such computations commonly failed (by several degrees of latitude) to account quantitatively for the observed cutoffs because the B-field models previously in use were not accurate enough. Puzzled investigators desperately postulated arbitrary diffusion models in order to account for the discrepancies. However, recent work by Pfitzer (1979) has shown that an improved B-field model is all that was ever required. The field model that he successfully used for computing cosmic-ray cutoffs, such as those illustrated in Table 1, is an unpublished improvement on the model of Olson and Pfitzer (1974). The new field model permits a realistic angle ($\zeta \neq 90°$) between the solar-wind velocity and the dipole axis, and (more importantly) provides a better global fit to the observed B field. Ring currents, tail currents, and magnetopause currents are included as before, but are modeled more accurately.

Debrunner et al. (1979) successfully utilized cosmic-ray cutoff calculations in conjunction with neutron-monitor data to determine the ring-current radius during a magnetic storm. Darchieva et al. (1978) had previously made an observational study of the variation of cutoff latitude with ring-current intensity during major geomagnetic disturbances. Other important trajectory studies include purely theoretical works involving neutral points (Amano and Tsuda, 1978) and current sheets (Cowley, 1978). Gall and Bravo (1979) have made significant studies of solar-proton trajectories in the geo-

Table 1. Observed and computed cutoff latitudes for 5-MeV protons in various field models, as summarized by Pfitzer (1979).

Model (Reference)	Midnight	Dawn	Noon	Dusk
Gall et al. (1968)	68°		72°	
Olson (1970)	69°		74°	
Olson-Pfitzer (1974)	66°	70°	69°	71°
Pfitzer (1979), $\zeta = 55^\circ$	65°	67°	68°	67°
Pfitzer (1979), $\zeta = 90^\circ$	$\underline{66^\circ}$	$\underline{67^\circ}$	$\underline{70^\circ}$	$\underline{67^\circ}$
Pfitzer (1979), $\zeta = 125^\circ$	66°	67°	68°	67°
Observations, extrapolated to $\zeta = 90^\circ$, $K_p = 0$	$66.4^\circ \pm 0.4^\circ$	$67.5^\circ \pm 0.9^\circ$	$70.4^\circ \pm 0.6^\circ$	$67.5^\circ \pm 0.6^\circ$

magnetic tail. Detailed trajectory studies of charged-particle motion near the magnetopause would be quite welcome, now that one has access to three-dimensional velocity-space distributions (Frank et al., 1978; Williams et al., 1978) from GEOS and ISEE.

The foregoing processes entail no change of particle identity. However, Blake and Friesen (1977) have described a mechanism whereby an incident heavy ion (O^+, for example) is stripped of one or more of its remaining electrons as the incident ion grazes the atmosphere near a magnetic mirror point somewhere above the cutoff latitude for particles of that rigidity. By virtue of becoming multiply charged, the ion thus has its rigidity greatly reduced and becomes trapped in the geomagnetic field. There is even a good chance that the ion subsequently has a small enough gyro-radius to obey the laws of adiabatic charged-particle motion.

ENERGETIC-PARTICLE TRANSPORT IN THE MAGNETOSPHERE

The technical definition of transport is the violation of one or more of the adiabatic invariants of charged-particle motion. Transport can be either diffusive or frictional in character and is described by means of the Fokker-Planck equation. One-shot processes such as charge exchange or the beta decay of a neutron are handled by adding source and loss terms to the Fokker-Planck equation for a species. Other processes that may change the particle flux at a given energy, but which conserve all three adiabatic invariants of charged-particle notion, are kinematical in character and are treated as such in the present work.

Lyons and Williams (1980) have recently found that one can account for the storm-time ring current by "transporting" the quiet-time ring current sufficiently inward in L. No additional source of charged particles or energy would be required, as long as the "transport" process conserves the first two adiabatic invariants. The most likely transport mechanism for this, consistent with the laws of physics, is unsteady magnetospheric convection. The consequences of such transport, even if accomplished by a single impulsive enhancement of the convection <u>electric</u> field, are qualitatively similar to the consequences of enhanced radial diffusion.

For particles of much higher energy than the ring current, it is important to consider also the effects of <u>magnetic</u> impulses. As commonly modeled, the effects of magnetic and electric impulses scale differently with particle energy, charge state, and equatorial pitch angle (e.g., Cornwall and Schulz, 1979). In pursuit of this idea, Lanzerotti <u>et al</u>. (1978) have analyzed the spectrum of (presumably) large-scale geomagnetic noise at synchronous altitude (ATS-6). By evaluating the spectral density at particle drift frequencies, they have estimated the corresponding radial-diffusion coefficient there. The results of Lanzerotti et al. (1978) are model-dependent, of course, but this is a common hazard in space research. It is better to obtain a model-dependent result than none at all, provided that the model has a rational basis. Other predictions of such a model can subsequently be tested against a more comprehensive set of observational data.

Using a similar philosophy, Holzworth and Mozer (1979) have deduced a radial-diffusion coefficient from electric-field fluctuations measured on simultaneous balloon flights at six auroral-zone locations spanning 180° of longitude. In this case the major model-dependent assumption was that **B**-field lines are equipotentials of the electric field. Since this assumption is likely to fail in an auroral arc, it would perhaps have been better to fly the balloons at a lower magnetic latitude. However, measurements of this type are highly worthwhile, and the work of Holzworth and Mozer (1979) represents an important first step in the field.

Radial diffusion caused by magnetic or electric impulses is known to leave an additional signature on the affected charged-particle populations. Particles dispersed in L by an individual impulse are consequently organized in drift phase by virtue of Liouville's theorem, and this organization manifests itself in the form of drift-periodic echoes in the particle intensities. Chanteur et al. (1977, 1978) have made a systematic study of this effect and have confirmed its observational significance beyond any reasonable doubt. Belian et al. (1978) suggest that proton drift echoes may alternatively result from an "injection" event, by which they presumably mean either a new supply of particles admitted to the magnetosphere or a dawn-to-dusk electrostatic impulse that is confined to the night side of the magnetosphere. Such a possibility is difficult to deny, but it is not supported by the electron-echo observations of Chanteur et al. (1977, 1978).

The notion of "transport" should also include charge-state transitions caused by charge exchange between energetic ions and the earth's atmosphere. This process is described by coupling the Fokker-Planck equations that describe the evolution of phase-space densities for the various charge states of (for example) oxygen. Spjeldvik and Fritz (1978a) have carried out such calculations in order to interpret observational data (Spjeldvik and Fritz, 1978b) on heavy ions in the magnetosphere.

Charge exchange inherently displaces the guiding center of a geomagnetically trapped particle and thus also contributes to a novel form of radial diffusion. An extreme example of such transport is that which enables ring-current protons to traverse the whole trapping region as neutrals and appear again as ions at low altitudes on the magnetic equator. By alternately losing and regaining its charge in the dense atmosphere, a hydrogen ion/atom would thus experience a truly diffusive transport. For heavier ions the transitions among charge states other than zero lead to truly diffusive transport even at ring-current altitudes. The element of randomness is supplied by the gyrophase at which the charge exchange happens to occur, since this gyrophase determines the direction in which the guiding center is displaced.

Certain aspects of energetic-particle transport are complicated enough that numerical computation of the particle trajectories is required. For example, Smith et al. (1979) have numerically traced the drift of particles in the presence of a time-varying convection electric field, and Harel et al. (1979) have numerically computed the evolution of bulk properties of the hot plasma (self-consistently) in a model of magnetospheric substorms. This type of work has a bright future.

Pitch-angle diffusion is a transport process of direct relevance to particle loss from the magnetosphere. It is for this reason that recent developments in the field of pitch-angle diffusion are discussed in the next section rather than here.

ENERGETIC-PARTICLE LOSS PROCESSES

A major loss mechanism for energetic particles in the earth's magnetosphere is pitch-angle diffusion into the loss cone. This occurs typically by virtue of cyclotron resonance between particles and a broad-banded spectrum of magnetospheric waves. The waves may be either electrostatic or electromagnetic, but the former tend to predominate outside the plasmasphere and the latter inside.

Waves in the magnetospheric plasma commonly originate from instabilities. Kaye et al. (1979) have considered the electromagnetic ion-cyclotron instability of ring-current protons subject to gradient-curvature drift and magnetospheric convection simultaneously. The instability is driven by pitch-angle anisotropy, as is well known. However, Kaye et al. (1979) have found that peculiar features of the growth-rate spectrum (in accord with observation) can be traced to specific cutoffs that are expected to appear in the phase-space density (see Figure 7) as the ring-current protons drift inward by convection from a source at L = 10. Contours of constant normalized growth rate γ/Ω_p at L = 4 are shown in Figure 8 for various source temperatures (γ = temporal growth rate, $\Omega_p/2\pi$ = proton gyrofrequency, $\omega/2\pi$ = wave frequency). It is significant, for example, that increasing the source temperature does not necessarily increase the growth rate. Only a small minority of the protons in a 4-keV Maxwellian are able to drift from L = 10 to L = 4 while conserving the adiabatic invariants of charged-particle motion.

Waves generated by instabilities such as that studied by Kaye et al. (1979) are expected to produce pitch-angle diffusion, which (in the presence of an atmospheric loss cone) results in local precipitation. The precipitation in this case occurs mainly in the

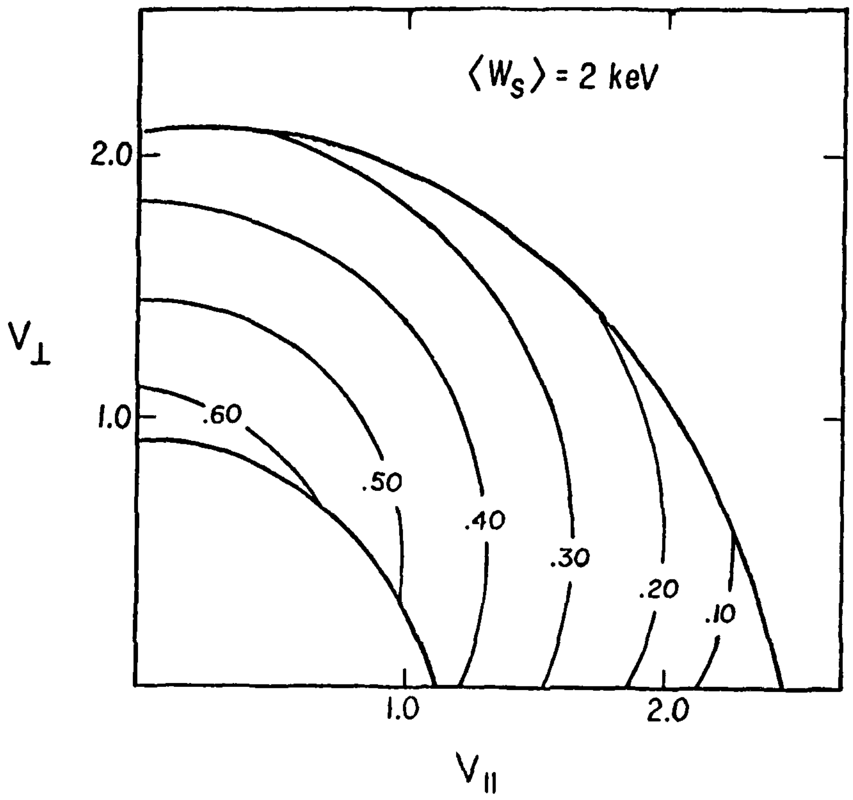

Figure 7. Contours of constant phase-space density at L = 4 (dusk meridian) for an isotropic source of temperature 2 keV placed at L = 10 in the presence of a 90-kV cross-magnetospheric potential drop distributed as $L^2 \sin \varphi$, where φ is the local time. The particles are protons, and the axes (as well as the contours) have been normalized arbitrarily (Kaye et al., 1979).

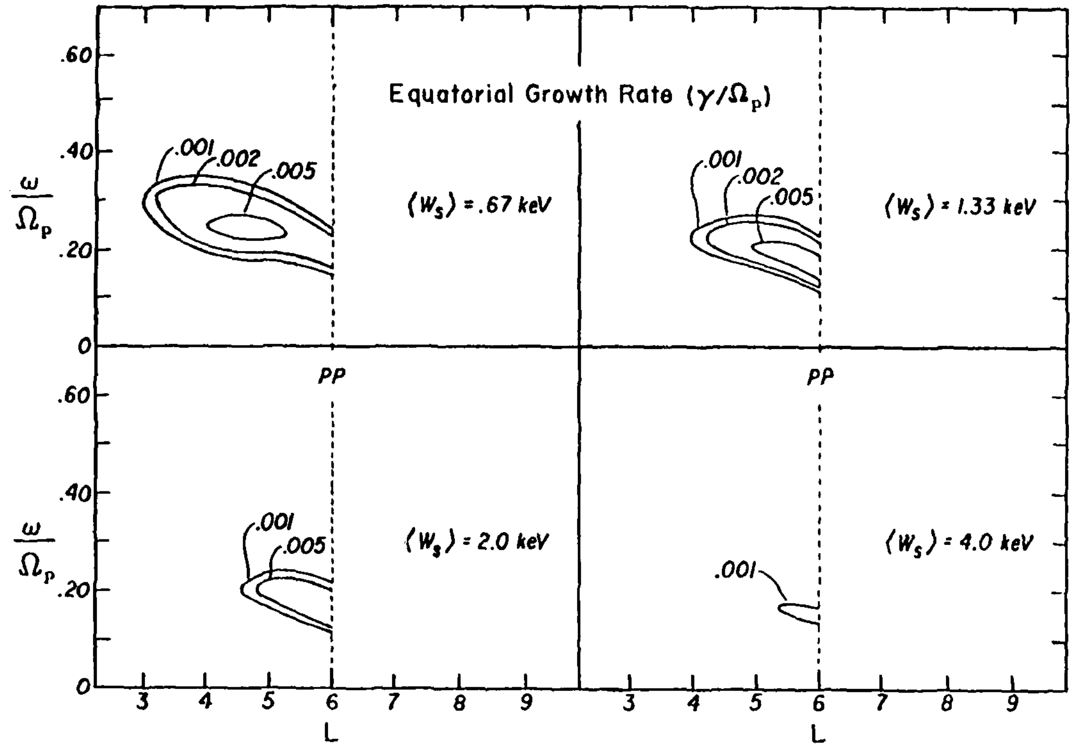

Figure 8. Equatorial growth rates for ion-cyclotron waves (electromagnetic) at L = 4 (dusk meridian), as computed by Kaye et al. (1979) for conditions described in Figure 7 and its caption, but with various source temperatures. Wave frequencies and growth rates are normalized with respect to the proton gyrofrequency, as indicated.

dusk sector, i.e., is organized with respect to local time. Vampola (1977) has found, on the other hand, that slot-region electron precipitation is organized with respect to geographic longitude (see Figure 9) if one averages over local time. Vampola (1977) suggests that precipitation maxima are associated with (and thus caused by) major VLF transmitters. It is difficult to test this idea statistically from the data in Figure 9, and it would have been better to use an earth-anchored magnetic longitude for organizing the data. However, the idea that anthropogenic processes actually lead to significant particle precipitation is indeed a provocative one.

A cleaner but more subtle example of transmitter-induced pitch-angle diffusion is shown in Figure 10 (Vampola and Kuck, 1978). In this case the authors observe a pitch-angle distribution that is truncated well outside the local loss cone at east (geographic) longitudes $> 100^{\circ}$. However, the equatorial pitch angle of the truncation consistently corresponds to the loss cone that would have prevailed (assuming precipitation at 100-km altitude) at longitude $54^{\circ}-62^{\circ}$ east (see Figure 10). The effect spanned a range of L values and energies, but each energy channel showed the effect as being centered on a different L value (see Figure 11) in the inner radiation zone. The interpretation of Figures 10-11 is that the electron distribution was largely free of pitch-angle diffusion at longitudes east of a powerful transmitter located at about $50^{\circ}-60^{\circ}$ east longitude. The variation of energy with L in Figure 11 is consistent with equatorial cyclotron resonance with an unducted 16-kHz signal for reasonable plasma-density models (Vampola and Kuck, 1978).

It is tempting but dangerous to infer from such evidence that the radiation intensity in the magnetosphere was much higher in the years before those powerful VLF transmitters were installed around the world. One might argue (Vampola, 1977) that the removal of a loss mechanism inherently (and in this case dangerously) elevates particle

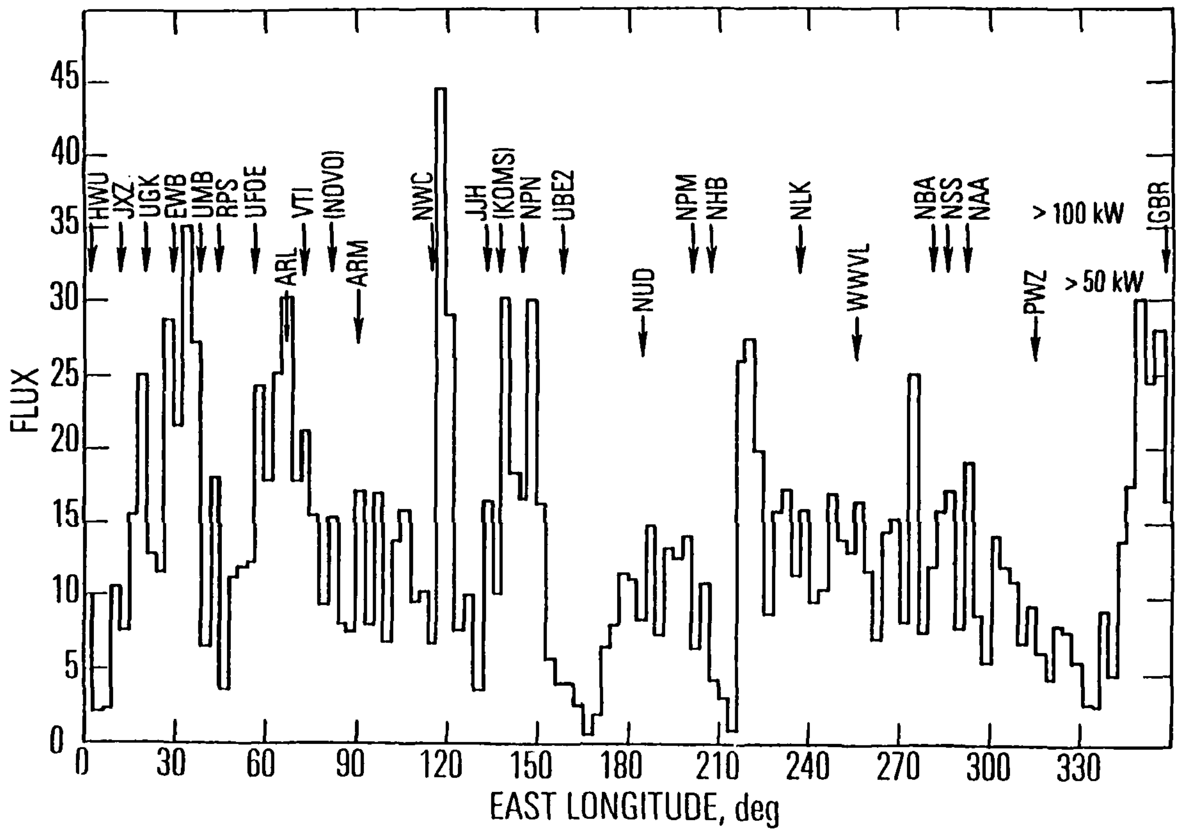

Figure 9. Average electron flux in the global loss cone during the year 1969 at energies 139-312 keV, L = 1.5-4.0 (Vampola, 1977). Also plotted are the longitudes of VLF transmitters with authorized power levels >50 kW and >100 kW.

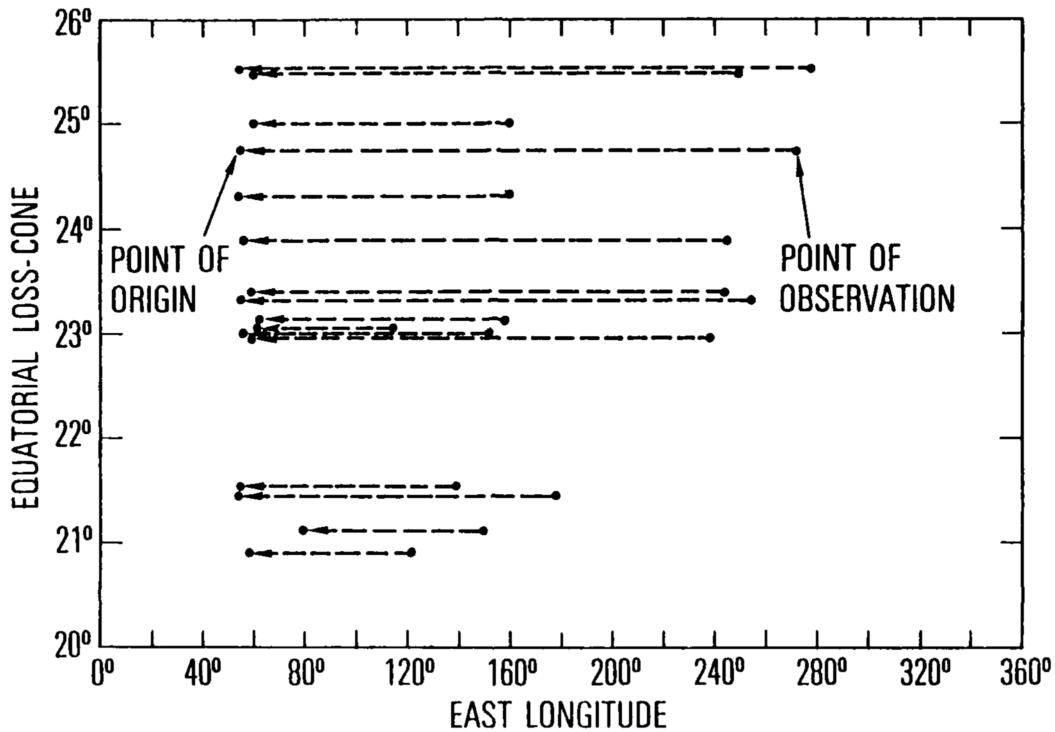

Figure 10. Mapping of local truncation in pitch-angle distribution to 100-km loss cone at smaller longitude (Vampola and Kuck, 1978). These OV1-19 results span a fairly wide range of L values: otherwise it would be very surprising (indeed impossible) to find such diverse truncation angles trace back to nearly the same longitude as loss-cone angles.

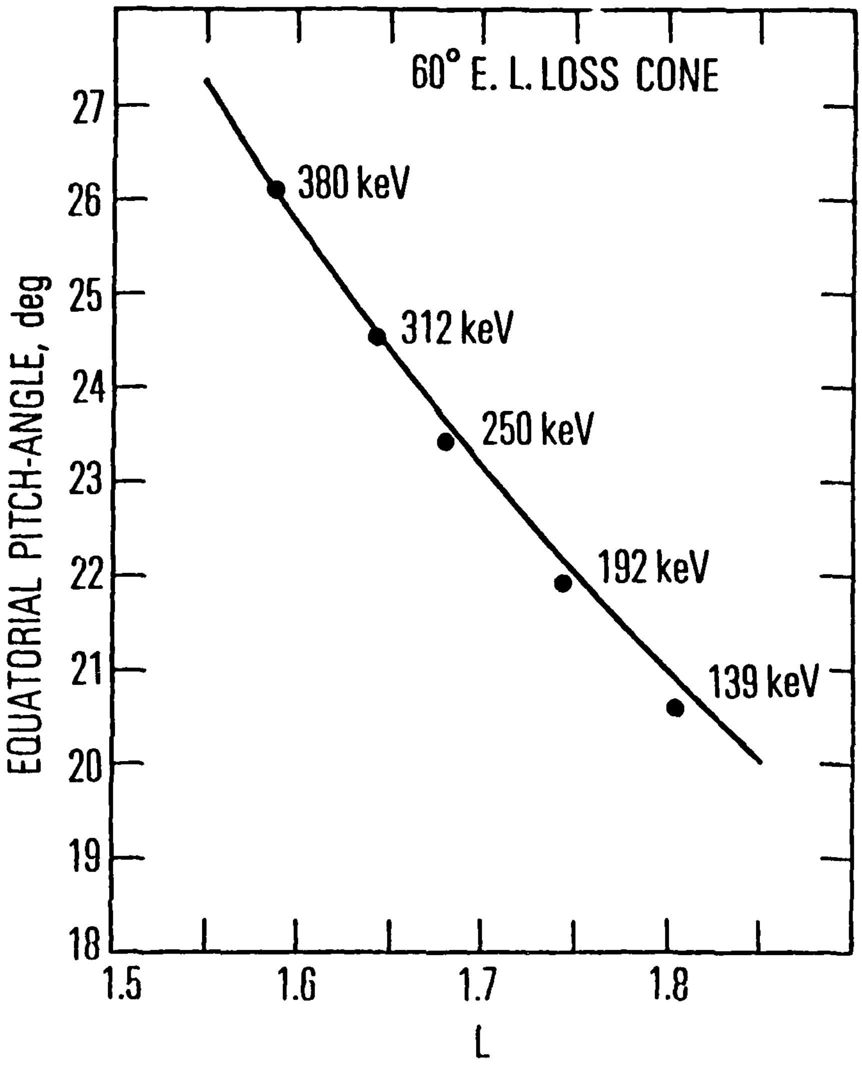

Figure 11. Dependence of equatorial pitch angle, corresponding to local truncation of pitch-angle distribution, upon L in the energy channel on which the effect is centered (Vampola and Kuck, 1978). For comparison, the solid curve represents the 100-km loss cone attained at a longitude of 60° E.

lifetimes. However, we need not conclude from the evidence that the transmitters do anything more than enhance the rate of pitch-angle diffusion at certain preferred longitudes at the expense of other longitudes. It is difficult to believe that the world's transmitters put nearly enough energy into the magnetosphere to account for the pitch-angle diffusion that occurs. The magnetosphere must have amplified their signals. This requires free energy, which is available in the anisotropy of pitch-angle distributions. Free energy in a plasma usually finds a way of expressing itself. If there are no transmitted signals to amplify, the plasma will tend to produce a broad-banded hiss through instability. On the other hand, if the free energy is spent on amplification of discrete signals, then the amount available for generating hiss will be reduced. In microscopic terms, the velocity-space diffusion caused by the amplified signals at preferred longitudes will result in a plateau on the particle distribution. The distribution thus modified is stable, and so it fails to generate hiss as the particles drift (through gradient-curvature effects) to longitudes east of the transmitter.

Actually, the whole idea that man-made transmissions account for significant particle precipitation is quite controversial. Vampola and Kuck (1978) strongly favor the idea in view of studies described above. Park and Helliwell (1978) and Luette et al. (1979) implicitly support the idea through their studies of power-line-harmonic radiation and its effects on magnetospheric chorus. However, Tsurutani et al. (1979) argue that power-line harmonics are dynamically unimportant. Imhof et al. (1978) argue that the pitch-angle diffusion process has no significant dependence on geographic longitude. Lyons and Williams (1978) argue that anthropogenic processes act only as minor perturbations on a dynamical system that is controlled mainly by natural processes. Thus, if one is not interested in (for example) the azimuthal structure or detailed energy-latitude dependence of particle precipitation, the effect of VLF transmitters may seem unimportant since the total amount of precipitation is not greatly enhanced thereby. However, if one is interested primarily in the fine-structure of particle precipitation, then the effects of VLF transmitters and power lines may seem very important indeed.

The change in equatorial pitch angle, caused by resonance between a particle and a coherent wave packet, is strictly diffusive only in the small-amplitude limit. A numerical and analytical study by Inan et al. (1978) covers the more general case in which the wave amplitude itself is large enough to trap particles in resonance, despite the inhomogeneity of the earth's magnetic field. Such trapping is necessarily of finite duration, but it leads to a nonlinear relationship between the cumulative change $\Delta\alpha_{eq}$ in equatorial pitch angle and the amplitude of the wave. Representative results for electrons resonant with the wave as they cross the equator are shown in Figure 12, where ϕ_o denotes the initial gyrophase of the particle relative to the wave.

Results of this type are relevant for the interaction of VLF transmissions and power-line harmonics with geomagnetically trapped electrons. A related topic is the interaction of such electrons with discrete signals of time-varying frequency, e.g., whistlers and chorus elements. The nonlinear response that is evident in Figure 12 for signals ≥ 5 mγ should serve as a warning against the uncritical application of quasilinear diffusion theory in such cases, even though the frequency spectrum appears to be smooth when averaged over time.

Other investigations of nonlinear effects have included the theoretical work by Brinca (1978) on cyclotron-resonance broadening and the numerical simulations by Papadopoulos and Rowland (1978) on the formation of auroral electron energy spectra. Moreover, Cornilleau-Wehrlin and Gendrin (1979)

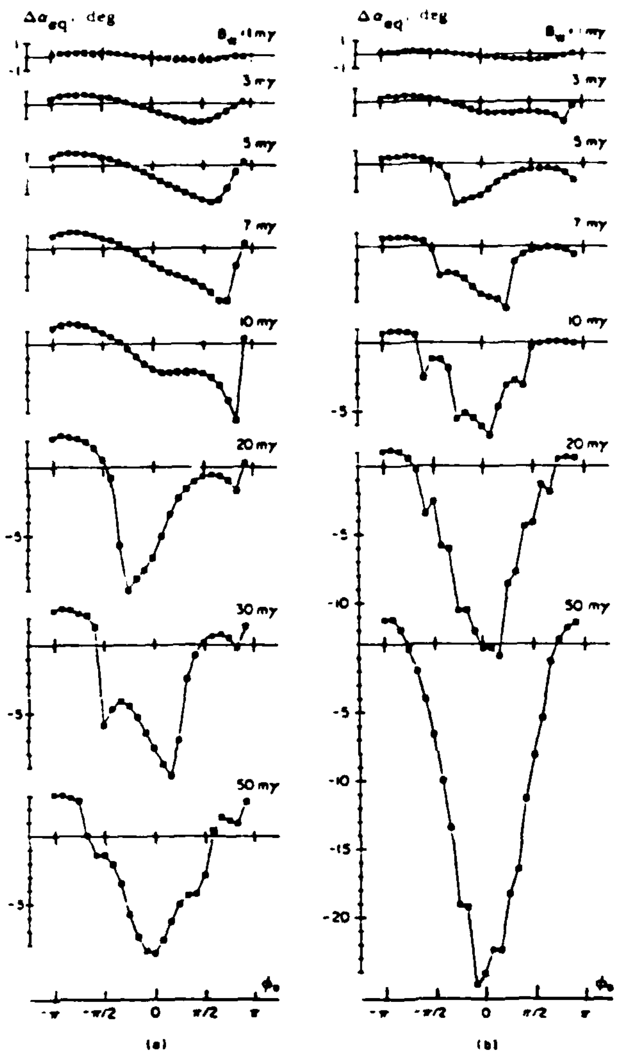

Figure 12. Total change in equatorial pitch angle accumulated by electrons of various initial phases ϕ_0 after interaction with whistler-mode wave of specified amplitude at L = 4 (Inan et al., 1978). Left panel: $\alpha_{eq}^{(0)} = 10^o$; right panel: $\alpha_{eq}^{(0)} = 30^o$; particle energy: that required for equatorial resonance with the 5-kHz wave.

have reported the observation of transmitter-induced quiet bands in the VLF noise spectrum and have interpreted this phenomenon in terms of nonlinear wave-particle interactions in the inhomogeneous $\underset{\sim}{B}$ field. Meyerson and Pokhotelov (1978), and also Meerson and Sasorov (1979), have described nonlinear bounce-resonant interactions between waves and particles. The inhomogeneity of $\underset{\sim}{B}$ has likewise been important in linear-instability studies. Hasegawa (1979) has considered the bounce-resonant excitation of Alfven waves by electron beams, while Bhatia and Lakhina (197[illegible]) have studied the drift-wave instabilities associated with the radial inhomogeneity of the ring current and plasma sheet. Buloshnikov <u>et al.</u> (1978) have studied proton-bounce effects on the generation of long-period geomagnetic pulsations.

The effect of an inhomogeneous $\underset{\sim}{B}$ field could possibly affect linear growth rates, even on time scales short compared to the bounce period, by broadening the cyclotron resonance between waves and particles or by other equilibrium-trajectory effects (Lundin and Shklyar, 1977). The presence of an electric field parallel to $\underset{\sim}{B}$ could similarly alter the linear growth rate. Ponyavin and Sazhin (1978), and also Misra <u>et al.</u> (1979), have studied the whistler-mode instability in the presence of such an electric field. Other investigators have focused instead on describing the Vlasov-equilibrium distribution more realistically than before. Thus, Kaufmann <u>et al.</u> (1978) have used the <u>observed</u> auroral-electron distribution (rather than a bi-Maxwellian simulation of it) for calculating the properties of electrostatic instabilities. Ashour-Abdalla and Kennel (1978a, b, c) have emphasized the effects of co-existing hot and (nearly) cold plasma components on electrostatic instabilities. Kiwamoto (1979) and Curtis and Wu (1979a, b) have emphasized the importance of gyroharmonic resonances for the case of oblique propagation.

Boswell (1978) and D'Angelo (1977) have especially considered instabilities that occur in the auroral region and polar cusp (otherwise known as the polar cleft). Finally, in work similar to (but less accurate than) the above-described work of Kaye et al. (1979), Solomon and Pellat (1978) considered the effects of magnetospheric convection on the Vlasov-equilibrium distributions of hot-plasma constituents and (consequently) on the linear growth rates of electromagnetic cyclotron waves.

KINEMATICAL EFFECTS

It is well known that energetic outer-zone electrons have a peculiar pitch-angle distribution on the night side of the magnetosphere, such that the maximum particle flux occurs at equatorial pitch angle α_o^* and $\pi - \alpha_o^*$ different from $\pi/2$ (e.g., West, 1979). This phenomenon was traced long ago to the properties of adiabatic drift shells in an asymmetric $\underset{\sim}{B}$ field. Recently, Baker et al. (1978) have successfully used the particle anisotropy as a measure of the day-night asymmetry of the magnetosphere, i.e., as an indicator of the strength of the tail current, in an effort to predict the occurrence of geomagnetic substorms. Moreover, Luhmann and Schulz (1979) have described especially simple methods for extracting quantitative parameters from the observational data in this context. Kosik (1979) has shown how to use similar methods at particle energies for which the convection electric field must be taken into account. Whipple (1978, 1979) has demonstrated the utility of a new "coordinate" system called (U, B, K), in which the adiabatic trajectories of nonrelativistic particles are straight lines under such circumstances. The trajectories turn out to be parabolic for relativistic particles, and so the (U, B, K) system constitutes a major simplification from traditional systems even in this case.

In a study of extensive data on outer-zone electrons from three of the ATS satellites, Paulikas and Blake (1979) have shown that the particle intensity in a given energy channel correlates well with the solar-wind velocity. A portion of this effect might well be attributed to adiabatic compression of the magnetosphere and a consequent energization of the particles observed. However, a cross-correlation analysis revealed a delay ~ 1-2 days between changes in the solar-wind velocity and changes in the particle fluxes. This suggests a gradual energization of particles by processes that a solar-wind enhancement can trigger, especially when the southward component of the interplanetary $\mathbf{B}$ field is positive (e.g., Akasofu, 1977). Thus, it seems that adiabatic and non-adiabatic effects (i.e., kinematical and dynamical effects) can occur in combination and thereby present a serious challenge to investigators whose duty it is to provide a quantitative description of radiation-belt processes.

EPILOGUE

The foregoing pages offer a sample of recent developments in the study of energetic particle populations and cosmic-ray entry with respect to the earth's magnetosphere. It would not be feasible to cover all areas of progress, and the selection of topics has been largely arbitrary. However, an effort has been made to treat topics that represent significant new directions in research. Equally important progress has been made by investigators working along more traditional lines. It is inevitable in a report of this type that mention of some significant contributions to the field has been omitted, but it is hoped that the topics covered are at least representative of recent progress in this area of space research.

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Many more papers on energetic particle populations and cosmic-ray entry have appeared during the past two years than could be cited in the above text. The author has compiled a supplementary list of relevant works from this period, a list that is meant to be representative but not necessarily exhaustive.

Each paper has been identified with one or more general subject categories as follows: (a) inner belt; (b) outer-belt protons; (c) outer-belt electrons; (d) diffusion, wave-particle interactions; (e) injected and/or drifting particles; (f) trapped ions, $Z \geq 2$; (g) solar cosmic-ray entry; (h) theory; (i) artificial perturbation of trapped particles; (j) general.

In accordance with the terrestrial orientation of IAGA Subdivision III-4, attention in the main text and in the supplementary bibliography has been restricted to the <u>earth's</u> magnetosphere.

Page numbers in translated journals are specified for the English (E) edition if available, otherwise for the Russian (R) edition. The list includes publications in major refereed space-science journals, as well as other materials that have come to the author's attention. No effort was made to search unrefereed journals, collections of abstracts, internal documents, and similar materials. The author apologizes for any omissions but recognizes that omissions are unavoidable in a task of this scope.

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LABORATORY OPERATIONS

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