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ADVANCES IN MAGNETOSPHERIC PHYSICS 1971 - 1974: ENERGETIC PARTICLES*

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ADVANCES IN MAGNETOSPHERIC PHYSICS 1971 - 1974: ENERGETIC PARTICLES

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ABSTRACT

An account is given of energetic particle resear h in magnetospheric physics for the time period 1971-1974. Emphasis is on relating the various aspects of energetic particles to magnetospheric processes.

Introduction

Historically, energetic particles have been considered to be those greater than about 45 keV. Although we find it necessary occasionally to consider lower energy particles, we generally adhere to this criterion. Major steps forward have been made in the last four years. We know now that the high-energy component of the trapped proton flux in the inner belt is due to the cosmic-ray-albedo-neutron decay source as had been predicted earlier. The radial and pitch-angle diffusion of electrons within the plasmasphere, driven respectively by electrical fluctuations and whistler-mode radiation, are understood well enough to predict experimental pitch-angle distributions and equilibrium radial profiles of the inner and outer belts, including the energy dependence of the slot position. The dynamics of the plasmapause have been partially established and the role of the plasmapause in stimulating a variety of wave-particle interactions (electromagnetic ion-cyclotron and whistler-mode wave-particle interactions) is well appreciated. However, the role of the electrostatic waves in wave-particle interactions has been only slightly explored as an aspect of magnetospheric dynamics. Substorm research has received major attention. Although it is the low-energy particles that provide the major interactions with the associated electric and magnetic fields during substorms, we find that the higher energy particles serve as tracers of the magnetic field topology. Such studies have been carried out in the magnetotail and in the low-altitude regions of the auroral zone. Finally, a large effort has occurred in the study of solar particle entry into the magnetosphere. Here again, the central theme has been the use of particles as probes of field topology. These solar-particle-entry studies along with the substorm studies argue convincingly for an open magnetosphere.

We discuss this work in greater detail in the following pages. For the most part, the division into the chosen categories has served well. Occasionally, however, there is an overlap between categories but this provides for unification. Although an attempt was made in this report to include papers in press or presented at recent conferences, and not yet published, this effort is incomplete; hence, some of the last part of 1974 is missing. There is also some work of a general nature which we do not categorize.

First we wish to cite the previous quadrennial report by Neil Brice [1971] covering the period 1967-1970. This one report covered all aspects of space physics for that period. Williams [1971, 1972] has written two general reviews of trapped particles extending back to the inception of space science; they provide a good historical overview. Schulz [1974] has written a review on trapped radiation concerning critical advances during 1970-1973 which provides enough theoretical background to satisfy the most fastidious researcher. A comprehensive book, Cosmical Geophysics [1973], has been published by the Scandinavians and covers the major advances in magnetospheric and auroral physics. This is an important book for expert and student alike. Finally, the National Space Science Data Center has generated a series of reports on trapped particle populations, taking advantage of a variety of earlier data sources. These are all included in the first bibliography.

The Inner Belt

An outstanding problem of the inner belt has been the source of the high-energy trapped protons. The cosmic-ray-albedo-neutron-decay source (Crand) has always seemed to be the most likely cause of the protons. However, early estimates by Lingenfelter [1963] of the neutron flux at the top of the atmosphere were too low by more than an order of magnitude.

It was not until the work of the group at the University of California at Riverside that adequate measurements of the neutron albedo (10 to 100 MeV) were made [Preszler et al., 1972; White et al., 1973], that later included angular distributions [Preszler et al., 1974]. The measured neutron flux was transformed to an injection current for trapped proton fluxes following the work of Dragt [1971]. Clafin and White [1973] compared the Crand source to experimental measurements of trapped proton fluxes [cf., Hovestadt et al., 1972a; Valot, 1972]. Following the work of Farley and Walt [1971], their diffusion analysis included terms for source, loss, and the effect of the secular change in the earth's dipole moment, besides the usual diffusion term. Loss was by coulomb interactions including nuclear interactions at the higher energies. The effect of the earth's decreasing dipole moment had been previously described by Heckman and Lindstrom [1972], Schulz and Paulikas [1972], and Farley et al. [1972]. The excellent agreement of the diffusion analysis in relating the Crand injection to the experimental data provides convincing evidence that the Crand source is adequate at least for protons of $E > 30$ MeV and $L \leq 1.7$. This work is reviewed by White [1973]. More recent work in this area is that of Clafin and White [1974] and Croley et al. [1974]. The first paper analyzes the diffusion of protons down to 2 MeV. Both papers indicate the need to include electrostatic as well as magnetic fluctuations in the diffusion analysis.

The inner belt electron population is no longer affected by the fission-decay electrons injected by the Starfish detonation. A high-energy residual population ($E > 1$ MeV) was found at $L \sim 1.4$ in 1968 by West and Buck [1974], but this in no way affects the observation of inner-belt dynamics. The electron inner belt is recognized to have a dynamic character not unlike the outer regions, except that the time scales [Stassinopaulos and Verzariu, 1971; West and Buck, 1974] are more on the order of a year rather than a few days. Also, it takes major storms ($|Dst| \gtrsim 200$ nT) to cause much inner-belt injection, and these storms occur on the time scale of a year. Between these storms a continual inward flow seems to be occurring as is brought out later [Lyons and Thorne, 1973; Lyons and Williams, 1974].

Imhof et al. [1973, 1974] have observed interesting spectra of electrons precipitating east of the South American Anomaly. In the range $L = 1.47$ to 1.72 they find spectra peaking ~ 700 to 300 keV and following a power-law variation $E \propto L^{-n}$ with $n \sim 6.1$ to 6.7. They believe that the explanation lies in some wave-particle interaction as described in the next section.

Outer Belt Regions — Diffusion, Electrons, Wave-Particle Interactions

In this section we further consider the concepts of diffusion as a means to populate the inner magnetosphere (L < 5). We consider pitch-angle diffusion as well as the traditional third-invariant-violating radial diffusion. Cole [1971] has made a contribution to diffusion theory by considering the combined action of pitch-angle scattering and gradient-B drifting in the presence of large-scale electric fields; and Schulz [1974] has contributed to our understanding of the third-invariant-violating resonance processes during a particles azimuthal drift. Walt [1971a,b], Walt and Newkirk [1971], and Falthammer (1972] have examined the experimental evidence for diffusion. Most of the radial diffusion coefficient show the same general L dependence but often vary more than an order of magnitude in value. There is an obvious need to understand the mechanisms of diffusion in more detail, both during quiet times and following storm-time injection. Significant progress in this regard has been made in the last few years.

Lanzerotti and Morgan [1973] have attempted an understanding of the diffusion mechanisms for relativistic electrons by measuring the power spectra of magnetic field fluctuations, 0.5 to 20 mHz, on the ground at L = 4. The derived diffusion coefficients were found to vary markedly with the level of magnetic activity, but were found to be too small to account for satellite observations of diffusing particles.

During the main phase of a magnetic storm electrons with $E \gtrsim 1000$ keV are lost, and electrons at lower energies increase by several orders of magnitude in intensity. Various aspects of these changes are reported in Owens and Frank [1968], Carpenter et al. [1971], Parsignault [1971], West et al. [1973a], and Hausler and Sckopke [1974]. The low-energy increase is an important unsolved problem in magnetospheric physics. The lower energy electrons decay with e-fold rates of a few days, whereas the higher energy electrons grow in the order of a week before starting their decay at e-fold rates of a week or so. Thorne and Kennel [1971] and Lyons and Thorne [1972] have suggested that the loss of the $\geq$ 1000-keV electrons occurs just inside the plasmasphere and is due to the resonant interaction with electromagnetic ion-cyclotron waves generated by the hot storm-time ring-current protons as they encounter the plasmasphere; the doppler shifted waves can interact with only the more energetic particles having a sufficiently positive pitch-angle anisotropy and an $E_{\parallel}$ which is greater than the magnetic energy per particle. A fairly direct confirmation of this pitch-angle diffusion comes from the low-altitude observations of precipitation by Vampola [1971a]. However, Hausler and Sckopke [1974] do not think that these concepts are necessary to explain their data.

The problem of pitch-angle diffusion inside the plasmasphere has been analyzed theoretically by Lyons et al. [1971], Lyons [1972], and Lyons et al. [1972]. These are calculations in which electrons interact with waves produced by other particles, i.e., parasitic interactions. They find it important in these calculations to include whistler-mode radiation propagating at a wide range of angles thus bringing in the higher order cyclotron harmonics. They also use the experimentally determined spectrum of whistler-mode radiation, ELF hiss; this leads to energy- and L-dependent pitch-angle distributions and pitch-angle diffusion lifetimes which agree reasonably well with experiment. The pitch-angle confirmation comes from Ogo-5 data [West et al., 1973a,b] and Explorer-45 data [Lyons and Williams, 1974].

Analysis of the charged particles in the post-recovery period following a storm has been a central problem of diffusion theory. Tomassian et al. [1972] analyzed electron data obtained aboard the OV3-3 satellite during the September 2, 1966 storm, and found that the radial diffusion could be explained through large-scale convective electric fields of amplitude 0.28 mV/m with a period of 1600 sec. Subsequently Lyons and Thorne [1973] attempted the more complete transport problem allowing radial diffusion to proceed via large-scale convective E-fields and loss via turbulent pitch-angle scattering and coulomb interactions. The generated radial profile (L ~ 1.2 to 5.5) of energetic electron fluxes is in rather good agreement with equilibrium profiles for a wide range of energies [e.g., Lyons and Williams, 1974]. It should be noted that the calculations are rather simplistic at this stage; e.g., they bypass completely the problems of wave self-excitation and reflection.

Etcheto et al. [1973] have attempted the self-consistent calculation of wave generation and particle diffusion. Their work is based on the early work of Roux and Solomon [1971] (also see Gendrin [1972]). The wave spectrum and electron distributions were calculated by an iterative process. However, the analysis pertains only to waves propagating along the field lines and to electrons ~ 40 to 160 keV. Some of the concepts introduced by Kennel and Petschek [1966] are more precisely defined, especially in regard to the limiting flux; e.g., just increasing the cold plasma density does not necessarily decrease the limiting flux of hot particles. Comparison of their theory with experimental data shows reasonable agreement.

Occasionally we have the chance to study pitch-angle diffusion more directly. Kuck [1974] studied the electron injection spike at L = 1.75 to 2.5 resulting from a Russian high-altitude nuclear detonation. He explains the results through diffusion by whistler-mode waves. During a rocket flight (L = 3.8), Rycroft [1973] obtained observations of an energetic-electron enhancement at the same time that a two-hop whistler was observed on the ground. In a study of phase disturbances to long-distance mid-latitude (L = 2 to 4) VLF transmission during a magnetic storm, Poterma and Rosenberg [1973] found that their data can best be explained through cyclotron resonance with energetic trapped electrons. They suggest that VLF propagation can serve as a useful tool for the detection of low-intensity electron precipitation. Imhof et al. [1974a] have observed peaks at 200 to 500 keV in the energy distributions of electrons precipitating from the slot region. They point out that the whistler-mode plasmaspheric-hiss frequencies, required to account for the peaks in terms of first-order cyclotron interactions at the equator, are consistent with measurements. Imhof et al. [1974b] have recently obtained measurements from the low-altitude polar-orbiting satellite 1972-076B of bremsstrahlung from electron precipitation events. This approach for measuring electron precipitation promises to be a valuable tool for the study of wave-particle interactions.

A number of papers have attempted to correlate the detection of waves with energetic particles. Burton and Holzer [1974] report Ogo-5 measurements in the outer magnetosphere of chorus which correlate with the pitch-angle anisotropy of energetic electrons. Holzer et al. [1974] made measurements of ELF chorus and of precipitating electrons > 45 keV on the low-altitude polar-orbiting Ogo-6 satellite, both the chorus and the precipitation consist of sharp peaks, which do not generally coincide, although they sometimes appear associated. They propose that the two effects are causally related by suggesting that the chorus is deflected away from the ducting field line within 1 R_E of the earth. Electron effects, explained by electrostatic wave interactions, have been reported by Nishihara et al. [1972] and Scarf et al. [1973]. In the latter paper, electrons > 50 keV abruptly decreased when low-energy electrons (1 - 4 keV) were detected near midnight at L ~ 5 - 6 at mid-latitudes accompanied by intense VLF electrostatic waves. The measurements were made at the shifting boundary between the plasmapause and outer radiation belt, and are interpreted in terms of field-aligned currents.

Azimuthal Effects - Injected Particles, Drift-Shell Splitting

The effects of the azimuthal-drift motions of energetic protons and electrons are very much apparent for particles of all energies during both quiet and disturbed periods. For the lower energy particles the effect of electric fields is often dominant, such as following the injection from a substorm or magnetic storm. (We only briefly mention the low-energy results because they are covered more completely in another paper of this report.) Low-energy protons in the keV range can actually drift eastward because of the existence of corotational and convective electric fields. Higher-energy protons drift westward to form the ring current. For electrons the effects of magnetic and electric field drift are in the same direction. Extensive measurements of the drift effect of substorm-injected particles have been made, e.g., DeForest and McIlwain [1971] and Sharp and Johnson [1972]. McIlwain [1972] has proposed a static electric field model derived from ATS-5 observations of 1- to 50-keV particles. Bogott and Mozer [1974] have made ATS-5 measurements of substorm-injected electrons (40 to 120 keV) and protons (60 to 165 keV). They concluded that, for the higher energy particles (≥ 75 keV), the dispersion observed in the arrival time of the various energy groups can be explained by gradient and curvature drifts alone. For the lower energy particles they had to look to other mechanisms to explain the drifts. Williams et al. [1974] have studied the drift motions of protons (1 to 300 keV) and electrons (1.5 to 560 keV) obtained on Explorer 45 (apogee 5.5 R_E) following substorm injection. They found that although the McIlwain [1972] E3 static electric-field model explained the particle drift effects, it was unable to explain the injection; transient electric fields must be considered. More recently Konradi et al. [1974] have reported complementary findings using Explorer-45 data. Their analysis suggests an injection boundary whose proximity to the earth extends several R_E tailward.

The Minnesota group has made numerous measurements on ATS 1 of substorm-injected energetic electrons [cf., Lezniak and Winkler, 1970; Erickson and Winkler, 1973; Erickson et al., 1974]. The measured electrons (50 to 1000 keV) are too high in energy for their azimuthal drift motions to be affected by the magnetospheric electric fields, so they are concerned mainly with the magnetic field distortions. These electrons, used as tracers of the field configuration, indicate the existence of a fault line west of which substorms are accompanied by a tail-like configuration and east of which the field is more dipole-like.

Recently, there have been a number of theoretical papers treating the azimuthal drift motion of energetic particles in more detail. Roederer and Hones [1974] were able to reproduce much of the ATS-5 data of DeForest and McIlwain [1971] by means of a time-dependent electric field (treated only E > 10-keV electrons). Kivelson and Southwood [1974a, b, c] have further analyzed the effects of the magnetospheric electric field on the particles: paper (a) analyzes the local-time variations of particle distributions which can be produced by the sudden enhancement of a cross-tail electric field; paper (b) re-examines the deviation of a particle from its dipole magnetic drift shell in the presence of an electric field (see Stern [1971] for earlier work); and (c) analyzes the convection boundaries associated with the enhanced cross-magnetospheric electric fields occurring during the early stages of magnetic storms and substorms and was effectively used in the analysis of some Explorer-45 data. Walker and Kivelson [1974] report computer studies of the energization of energetic electrons along their trajectory as they drift through the nighttime at the time of a sudden cross-tail electric-field enhancement. Through this approach they were able to provide an improved interpretation of the > 50-keV electron data obtained on ATS 1 and 5 by the Minnesota group.

There also have been several significant theoretical papers on the drift motions of energetic particles in a distorted magnetosphere to produce drift-shell splitting [Shabansky, 1971, 1972; Kosik, 1971; Antonova, 1972; Roederer, 1972; Schulz, 1972; Alekseyev, 1973; Roederer et al., 1973]. All the above papers discuss particles in guiding-center motion along the field lines. In the magnetotail neutral-sheet region we encounter another mode which has been described by Speiser [1971, 1973] and Sonnerup [1971]; in its simplest form it is the sinusoidal-like looping motion of the particles, as they encounter the field reversals on either side of the neutral sheet while drifting azimuthally across the magnetotail. Sonnerup presents additional modes.

Most of these theoretical ideas have been confirmed by observations. Energetic-particle pitch-angle observations in the near equatorial regions have been made by Bogott and Mozer [1971] at the geosynchronous orbit, and West et al. [1972], West et al. [1973a,b], Buck et al. [1973], and West and Buck [1974] at distances to the magnetopause and well into the magnetotail. Bogott and Mozer have presented temporal variations of electron and protons obtained on ATS 5 as a function of local time and magnetic activity. They observe shell-splitting effects and find evidence of loss-cone filling during substorm particle injection. Buck et al. present proton pitch-angle changes during a substorm. The rest of the papers are on energetic electrons. The picture for the eastward-drifting electrons is as follows: Pre-noon the normal loss-cone distribution extends to the magnetopause. Past noon, beyond the equatorial constant-B contour that maps from the magnetopause to ~ 7 R_E at midnight, the effects of shell splitting are especially pronounced, i.e., one sees the "butterfly" distribution. The shell-splitting effects become even more pronounced in the pre-midnight magnetosphere so that $j_\perp$ is often near background. As the eastward azimuthally drifting particles encounter the tail-like fields of the plasma sheet they change from guiding center motion to the looping mode of Speiser and Sonnerup. The finite field perpendicular to the sheet turns the electrons towards the earth where some precipitate and others mirror to return to the sheet to be again transformed to the sinusoidal looping mode. These effects occur during both quiet and substorm periods, but the distance into the tail where the effect begins depends strongly upon magnetic activity.

An interesting facet of the azimuthal drift motions involves the drift paths through the dayside high-latitude minimum-B regions [Shabansky, 1971, 1972; Antonova, 1972] Alekseyev, 1973. Possible experimental confirmation comes from the work of Murayama [1971], and Buck and West [1973].

Outer-Belt Regions — Protons, Ring Current, Wave-Particle Interactions

The population of high-energy protons decreases rapidly from the inner belt outward and is dominated by protons < 1 MeV in the outer-belt region. Imhof and Regean [1972] made low-altitude measurements from OV1-19 and found detectable fluxes of > 70 MeV protons to L ~ 2.2. In addition, they studied protons in the outer belt down to 1.2 MeV during the period from March 1969 to June 1970. A diffusion analysis of these data is consistent with previously published diffusion coefficients. Energetic protons to a few hundred keV are found out to the magnetopause where the intensity usually drops rapidly by several orders of magnitude. Kaufman and Konradi [1973] made use of measurements of > 140-keV protons from Explorer 12 to infer magnetopause boundary motions. They used the proton east-west effect to make essentially instantaneous measurements of the flux gradients and hence to separate space and time effects. The measured velocities were usually < 20 km/s. Generally, however, the major interest in outer belt protons in the last few years has been with the protons of < 100 keV which provide the main ring current effects. Typical spectra of these particles (ranging from 200 eV to 1 MeV obtained from OGO 5) have been reported by Pizzela and Frank [1971] and Pizzela and Randall [1971]. Presently Explorer 45 is providing detailed measurements of fluxes and pitch-angle distributions of protons 0.7 keV to 872 keV out to L = 5.3; these data are contributing greatly to the study of wave-particle interactions. Venkatesan and Krimigis [1971] have reported proton spectra of the higher energy outer belt fluxes ranging from 0.3 to 1.8 MeV.

During substorms and storms, hot ring-current protons (5 to 100 keV) are injected into the trapping regions from the night side of the earth [cf., Burns and Krimigis, 1972; Konradi et al., 1973; Smith and Hoffman, 1973]. According to the theoretical ideas of Cornwall et al. [1970], intense electromagnetic ion-cyclotron waves are generated as the hot protons encounter the plasmapause, resulting in pitch-angle scattering and a precipitation pattern which should lie predominately a few tenths of an L-shell inside the plasmapause. The necessary conditions for the instability are a positive pitch-angle anisotropy and a plasma density adequate to doppler shift the waves to the parallel motion of the particles. Despite the fact that there is only one experiment showing evidence of ion-cyclotron waves in this region of space [Taylor et al., 1974], the ideas are well-entrenched (these low-amplitude low-frequency waves present a difficult experimental detection problem). Cornwall et al. [1971a] have proposed a theory of SAR arcs based upon these ideas. Subsequently Cornwall et al. [1971b] observed precipitating protons which would seem to provide confirmation. However, Mizera [1974] and Søraas and Berg [1974] presented observations of 12- to 500-keV and 115- to 880-keV protons, respectively, showing the precipitation maxima to fall outside the plasmapause and generally extending out to the trapping boundary. Measurements of low-energy protons are reported, e.g., by Bernstein et al. [1974] showing the same results. Coroniti [1973], aware of earlier Mizera results, provided a critique of the theory of Cornwall et al. [1970,1971a]. He points out that the quasi-electrostatic ion-loss-cone mode is unstable for protons of large pitch-angle anisotropy [Coroniti et al., 1972] and becomes a candidate to explain the precipitation in the region beyond the plasmapause.

Despite the seeming inadequacies of the ideas of Cornwall et al. [1970] there is an abundance of Explorer-45 observations that indicates that ion-cyclotron instabilities are involved. These observations have been widely published; most are discussed by Williams and Lyons [1974a,b], Williams [1974a,b], and Fritz and Williams [1974]. They have made detailed pitch-angle measurements of protons which at the more extended distances indicate a wide, almost flat, pitch-angle distribution with a loss cone which changes rather abruptly to a $\sin^n\alpha$ distribution closer to the earth. Interpreted in terms of the ion-cyclotron instability, they obtain a reasonable N-vs-L variation. Furthermore, by this approach, they are able to determine the changes in the plasmapause position during post-storm recovery; this gives quite reasonable cold-plasma flux-tube refilling rates. Unfortunately they do not have a direct cold-plasma measurement to confirm that the changes in their pitch-angle distributions are indeed due to the onset of precipitation at the plasmapause.

More recent theoretical treatments of the proton precipitation problem have centered around finite-β effects [cf., Davidson, 1974; Perraut and Roux, 1974]. In the latter paper, theoretical computations of the ion-cyclotron growth rates in a mixture of hot and cold plasmas show that the most interacting protons are in the high-energy tail of the proton distribution ($\sim$ 30 keV at $L \sim 7$ to $\sim$ 120 keV at $L \sim 4$). In a complementary vein, Gendrin [1974] has attempted to obtain an overall picture of wave-particle interactions involving protons of 5 to 200 keV in different parts of the magnetosphere ($L = 3$ to 8).

Magnetospherically Trapped Ions, $Z \geq 2$

Other than holding intrinsic interest the ionized He, O, C, and N particles trapped in the magnetosphere, are valuable as probes of magnetospheric transport and loss processes. Currently the question is whether the particles are directly injected from the solar wind or polar wind, in which case the abundance ratio should not change, or whether the particles are the result of diffusion from a distant source region. Cornwall [1971, 1972] has developed a diffusion theory governing these effects. Radial transport is assumed to be driven by electrical fluctuations. Charge exchange and coulomb losses are included as loss processes, but the problem of pitch-angle diffusion apparently can be ignored. The radial diffusion coefficient is proportional to $\langle Z/A \rangle^2$ at fixed energy per nucleon (note that Z is the instantaneous ionic charge state) and this is invoked to explain why He, O and C diffuse more slowly than protons.

Van Allen and Randall [1971] have presented evidence from Injun-5 satellite data for the direct, durable capture of 1- to 8-MeV solar alpha particles onto L-shells 3.0 to 3.5 during the greatly disturbed period of October 29 to November 1, 1968. The fluxes rose almost two orders of magnitude above the normal flux and decayed away with a time constant of ~ 50 d. Minor injection occurred with other storms, all having in common the occurrence of appreciable alpha fluxes in the solar wind. Van Allen and Randall argue that direct injection occurs under special conditions.

Krimigis and Verzariu [1973] and Fennell et al. [1974] have provided the most recent and complete studies of the distributions of alpha particles in the magnetosphere. Krimigis and Verzariu analyzed the Injun-5 data after the storm-time injection decayed, i.e. mid-1969 to early 1970. They find that typical j_α/j_p values are ~ 2×10^{-4} when comparisons are made at equal energy/nucleon. Furthermore, they find reasonable agreement with the theoretical diffusion model of Cornwall [1972]. Fennell et al. [1974] studied alpha particles of energy 0.85 to 9.0 MeV at L = 2 to 4 during 1969 and reached much the same conclusions. Distribution functions of alpha particles and protons were nearly identical in slope and still rising at L = 4, indicating the source region to be farther out. All of these measurements were made somewhat off the equator. Recent results of Fritz and Williams [1973] at the equator for 0.225-0.500 MeV/nucleon give $j_\alpha/j_p \simeq 10^{-2}$ in line with solar-wind predictions. Although the Cornwall theory predicts an upturn at these energies, these preliminary results of Fritz and Williams seem to be at odds with the other data.

Mogro-Comparo [1972] has reported Ogo-5 observations of 13-33 MeV/nucleon ionized C,O, and possible N, trapped near the equator for $L < 5$ for 1968 and 1969. He finds that the fluxes are ~ 100 times greater than the solar-wind flux in the same energy interval. Also the abundance ratio is $O/C = 0.5 \pm 0.4$ which is consistent with only an extraterrestial source. This could indicate direct injection from the solar wind at a time of great enhancement, but is also consistent with the Cornwall [1972] theory. However, Blake [1973] does not consider this a definitive test of the diffusion theory because of the high energy of the particles.

Plasma Sheet and Magnetotail

Energetic electrons and protons (to several hundred keV) are found deep in the magnetotail. Discounting solar particles, these particles are generally confined to the plasma sheet on closed field lines, and hence are extensively used as tracers of the plasma sheet position. Such observations are quite useful in substorm research and have been used extensively by Vela investigators and others (cf., the references to Hones). Recent investigations pertaining more to general effects are the Explorer-35 observations of Meng [1971] at 60 R_E, the Imp-3 observations of Meng and Anderson [1971] out to 40 R_E, and the Ogo-5 observations to 24 R_E of Walker and Farley [1972], Aubry et al. [1972] West et al. [1973a,b], and West and Buck [1974]. The first three papers refer to general spatial distributions. Meng found that solar magnetospheric coordinates organized his data. He found a general flaring in the Y_{GSM}-Z_{GSM} plane away from midnight and an enhancement in the higher energy fluxes (> 45 keV) at dawn relative to dusk. Walker and Farley have provided the spatial distribution of $E \geq 50$ keV electrons. They found that the use of a neutral-sheet model, i.e., organization in terms of the Y_{GSM}-Z_N plane, greatly facilitated the data organization. Their contours of constant percentage of occurrence diverge only slightly away from midnight. West et al. [1973a] have studied the equatorial pitch-angle distributions of energetic electrons. As previously mentioned, the effects of drift-shell splitting cause an almost complete absence of $j_\perp$ in the distributions seen beyond ~ 9 R_E past dusk. However, past midnight the distributions are largely filled in at 90° pitch angles and tend towards isotropy; this change is often associated with substorm effects.

The phases of a substorm from satellite observations [McPherron, 1972; Russell and McPherron, 1973] involve (1) a growth phase during which the magnetic field becomes more tail-like, (2) an expansion phase associated with the negative bay, during which the field becomes dipole-like and expands outward, and (3) a recovery phase. Although the growth phase is controversial, it is clearly identifiable in Ogo-5 data during radial inbound passes near midnight. As the field becomes more tail-like during the growth phase it is found that energetic electrons showing the butterfly pitch-angle distribution abruptly becomes isotropic. This effect is attributed to the particles switching from guiding-center motion to the sinusoidal looping mode in the vicinity of the neutral sheet in association with the usual magnetic noise that is present in the sheet [West et al., 1973b; Kivelson et al., 1973; West and Buck, 1974]. That the appearance of isotropy is associated with precipitation is shown from the balloon measurements of Parks [McPherron et al., 1973a] during the August 15, 1968 substorm study. Ostensibly this is the sort of precipitation seen in the balloon x-ray study of Pytte and Trefall [1972] and the low-altitude-satellite electron studies of Rossberg [1971, 1972] and Rossberg et al. [1973]. During substorm recovery the pitch-angle distribution first tends towards isotropy followed by previously undisturbed electrons drifting in from dusk. Such strongly disturbed periods are expected to give rise to betatron acceleration and various wave-particle effects such as those observed by Kivelson et al. [1973] and Scarf et al. [1973].

During the extensive study of the August 15, 1968 substorm, protons were used to track the shape of the plasma-sheet boundary by means of the proton east-west effect [Buck et al., 1973]. At about 8 R_E near midnight the plasma sheet appeared to thin to no more than a few tenths of an R_E, which is interpreted by McPherron et al. [1973b] as evidence of strong near-earth reconnection just prior to substorm expansion. Palmer et al. [1974] have performed a somewhat similar analysis using 0.5- to 0.9-MeV solar proton data obtained on Vela 6A high in the north lobe of the magnetotail. At times of sudden flux changes they noted directional anisotropies which, when interpreted in terms of the east-west effect, indicated flow perpendicular to $\vec{B}$ towards the neutral sheet and electric fields of ~ 0.5 to 1.0 mV/m. This is the first measurement of convective flow in the lobes of the magnetotail.

Earlier magnetotail energetic-electron observations (a few 10's of keV) near the magnetopause [Meng and Anderson, 1970] have been extended to the high-latitude regions by Hones [1974] and Meng [1974]. Hones suggests that the boundary layer is the magnetic projection of the dayside cusp. It would appear that these results are associated with the boundary measurements of energetic electrons and protons (to an MeV or so) obtained by Heos-2 experimenters in the high-latitude, high-altitude magnetotail regions near the polar cap [Hedgecock et al., 1973; Domingo et al., 1973; Page et al., 1973; Domingo et al., 1974].

High-Latitude Near-Earth Effects — Auroral Oval, Boundaries, Precipitation

A very extensive and varied literature has evolved concerning this very important region of space. Although most rocket payloads include energetic particle experiments as well as low-energy particle experiments, the energetic-particle results are only of secondary importance to the particular mission and generally are not considered here. Also, papers based mostly on riometer measurements are largely excluded.

Pertinent reviews on the patterns of particle precipitation and the sources of Birkeland currents have been written by Paulikas [1971] and Arnoldy [1974], respectively. Energetic particles, being less affected by electric fields than the keV particles responsible for most of the auroral effects, are used extensively as boundary indicators. As a near-earth satellite moves to high latitudes, a point is reached where the energetic-electron counting rates drop rapidly to background. The Canadian group introduced the use of a 35-keV trapping boundary [McDiarmid and Burrows, 1968]. Similarly, the Iowa group has made extensive use of a 45-keV trapping boundary, and terms it a "natural coordinate" for studying magnetospheric phenomena since it appears to be scientifically meaningful for the discussion of many particle and electric-field effects [Ackerson and Frank, 1972; Frank and Ackerson, 1972; Gurnett and Frank, 1973]. Romick et al. [1974] have made use of a 130-keV trapping boundary with essentially the same results as for the lower energy boundaries; they also made use of the isotropic boundary [cf., Fritz, 1970]. Usually the isotropic boundary, useful in the nighttime magnetosphere, signals the inner edge of the plasma sheet. On the other hand, the trapping boundary ostensibly indicates the limit of closed field lines. Burrows [1974] has examined this point critically and suggests that the energetic-particle trapping boundary is not necessarily the limit of closed field lines, but instead is caused by wave turbulence in the plasma sheet at the most equator-ward of the extended arcs. He suggests the use of the term "turbulence boundary" rather than "trapping boundary." Frank [e.g., Ackerson and Frank, 1972] finds his low-energy inverted "V" events just poleward of the trapping boundary. Conversely, Burrows [1974] and Venkataragen et al. [1974] find the inverted "V" events just inside the trapping limit, and state that the events are occurring in the distant extension of the plasma sheet on closed field lines. There may be some subjectivity in the evaluation of the trapping boundary.

Many surveys have been made of the trapping boundary. The most recent is by Page and Shaw [1972a,b] who have analyzed some 4000 energetic-electron boundary crossings observed on the Esro 1/ Aurora polar satellite. They find the average noontime crossing to be 75.5° inv. lat., and the midnight crossing (2300 MLT) to be 69.5° inv. lat. with a variation of about ± 5°.

The discovery by Frank [1971b] of the "polar cusp" or "cleft," a dayside region of magnetosheath plasma entry lying between those field lines which connect on the dayside of the earth and those that are swept back into the tail, has introduced an important new aspect of magnetospheric dynamics. This discovery has led to many new speculations on plasma entry to the magnetosphere. Although the equatorward edge of the polar cusp may extend to 80° inv. lat. during quiet times, it was observed at ~ 43° by Ogo-5 instruments during the great storm of November 1, 1968 [Russell et al., 1971]. These Ogo-5 observations have provided a wide variety of wave and particle effects [Fredricks et al., 1973]. Burch [1972] has made an extensive study of the polar cusp and finds that the near-earth width can be several degrees wide in inv. lat. He also finds that the low-altitude boundary of electron precipitation at 0900 to 1500 MLT moves equatorward by several degrees during substorms; this is interpreted as the erosion of magnetic flux from the dayside of the magnetosphere and its transport to the tail during the growth phase of substorms. Complementary research on boundary motions is that of Frank [1971a], Hrûska et al. [1972], McDiarmid and Hrûska [1972], Kivelson et al. [1973], and Romick [1974], to cite a few.

In the last few years, extensive observation of energetic protons extending to several hundred keV have become available from the Esro 1 A and B satellites [e.g., Lindalen et al., 1971; Amundsen et al., 1972; Huage and Søraas, 1974]. The precipitation patterns were studied for a wide range of activity and local time in relation to the trapping boundary and promise to elucidate a wide variety of magnetospheric processes. As examples on the dayside, two precipitation zones are found during slight disturbances, the poleward zone showing an isotropic pitch-angle distribution and the equatorward zone showing an anisotropic distribution. On the nightside, isotropy is found near the trapping boundary, and anisotropic pitch-angle distributions peaked at 90° are found equatorward. The latter is probably associated with the ring current, and the isotropy is observed on field lines threading the neutral sheet. Søraas [1972] and Amundsen et al. [1974] have observed > 100-keV protons in the polar cusp, and have attempted to associate these protons with a sheath source.

Rossberg [e.g., 1971, 1972] has observed some interesting electron precipitation effects (E > 40 keV) in data obtained on the low-altitude, polar-orbiting satellite Azur. The measurements show that a sharp precipitation boundary may occur almost simultaneously before and after midnight, separated by as much as six hours in MLT and symmetrically disposed about 2300 MLT. In many passes, the sharp precipitation boundary is confined to a narrow MLT range before midnight, whereas in the midnight-to-dawn sector the electron flux decreases with increasing latitude accompanied by widespread precipitation. This asymmetric precipitation pattern occurs predominantly during the growth and recovery phases of substorms.

The balloon x-ray observations, e.g., Bjordal et al. [1971], Pytte and Trefall [1972], and Pilkington [1972], are probably associated with Rossberg's observations. Measurement of the x-rays provides a determination of electrons ≥ 30 keV precipitating into the upper atmosphere. Near midnight, smooth precipitation occurs during substorm growth phases. Impulsive precipitation often occurs at substorm onset followed by a general, enhanced precipitation relative to that occurring pre-onset. These observations along with those of Rossberg point up the need to know what is happening simultaneously in the equatorial plasma sheet and at low altitudes, and how the magnetic field lines map between the two regions.

Solar Particles in the Magnetosphere

There has been a great deal of activity since the suggestion by Michel and Dessler [1965] that low-energy cosmic rays could serve as probes of magnetospheric topology and help decide between the "open" and "closed" models of the magnetosphere. Research in solar particle entry to the magnetosphere has been especially prolific in the last four years, with each experimenter thinking up especially clever tests to check the magnetospheric models. Although the consensus of opinion is that the magnetosphere is open there are occasional observations that are explained equally well by a closed magnetosphere. This latter view is presented by Michel and Dessler [1974].

This research can be considered in terms of access to the various regions: (1) to the high polar-latitude (HPL) region on open field lines, (2) to the low polar-latitude (LPL) region of quasi trapping, (3) to the tail and neutral sheet, and (4) entry deep into the magnetosphere. This is a field of research replete with review papers; the most recent and pertinent is that of Paulikas [1974].

Turtle et al. [1972] measured the electron entry to the HPL region for the November 2, 1969 event finding a delay time of < 1 min. Considered in terms of direct access, entry is at < 600 R_E down the tail. They find that access to both polar caps is uniform and independent of the direction of the IMF; this is in agreement with measurements of West and Vampola [1971] on the April 1969 solar particle event. These latter data, obtained from the Ogo-5 satellite interplanetary and OV1-19 near the earth, show that solar electrons can enter the HPL region without loss of intensity, apparently undergoing adiabatic motion along the field lines. Vampola [e.g., 1974] has observed pitch-angle changes between the LPL and the HPL regions in which the distribution changes from a double loss cone, indicative of trapping, to a single loss cone, indicative of the inward streaming of solar electrons. Vampola [see West and Vampola, 1971] reports an example giving boundaries for 50-keV electrons at 64.9°, and for 1.1-MeV electrons at 64.4° inv. lat. Burrows [1972] reports Isis-1 data for electrons > 23 keV and > 42 keV. The pitch-angle anisotropies for the lower energy electrons clearly define the trapping limit, and the two energies together define the region of auroral precipitation; the precipitation region appears to be on closed field lines. This might become an important approach for substorm research. Evans and Stone [1972] obtained a total of 333 observations from the polar orbiting satellite Ogo 4 of the boundary of the polar-access region for electrons > 530 keV. These data provide a comprehensive map of the polar cap.

In contrast to electrons, protons show a large north-south asymmetry in their access to the HPL regions. The asymmetry for the protons is quite dependent upon the pitch-angle anisotropy of the interplanetary proton fluxes. The difference might be explained by the fact that the polar-cap observations are not available for those infrequent times when the interplanetary electron flux was anisotropic. Sectored proton data (> 0.3 MeV) were obtained by Injun 5 over the polar cap simultaneously with data obtained from Explorer 33 and 35 while in the interplanetary region [Van Allen et al., 1971; Fennell, 1973]. The HPL intensities tracked the interplanetary field-aligned intensities on an absolute basis. The tracking was in agreement with direct motion along a field line from the interplanetary medium to the polar cap about 90% of the time; if one polar-cap proton flux was high the other was low in agreement with the interplanetary anisotropies. In contrast, the LPL regions (quasitrapping) tracked the maximum fluxes (we explore this topic further in the next paragraph). Complementary measurements, showing the north-south asymmetry, are those of Domingo and Page [1971, 1972], Engelmann et al. [1971], and Scholer et al. [1972]. These data argue strongly for an open magnetosphere.

Adjacent to the open-field-line region of the HPL region we have the region of quasi-trapping in which the fluxes, clearly of solar origin, can be higher than in the HPL region. These fluxes are often seen coincident with auroral and trapped radiation. Significant work is that of Vampola [1971], Bewick et al. [1973], Scholer et al. [1974], Blake and Vampola [1974], and Hynds et al. [1974] to name but a few. Access to the quasi-trapping region is an obvious candidate for study in terms of diffusive access. However, most of the data seems to be best explained from access via the magnetotail and neutral-sheet regions. During a solar particle event the magnetotail is thoroughly invaded by energetic electrons and protons as shown, e.g., by Durney et al. [1972], Cooper and Haskell [1972], Domingo et al. [1974], and Willis et al. [1974]. The analysis of tail and near-earth data has involved considerable study of various magnetospheric models and trajectory analyses. Important contributions in this area are by Gall et al. [1971], Durney and Morfill [1972], Gall and Bravo [1973], and Scholer [1974a]. Morfill and Scholer [1973b] have written an extensive review of this work.

The rigidity of solar electrons apparently is too low to permit deep entry into the magnetosphere. However, the point is difficult to check because trapped electrons are present. On the other hand, solar protons are easy to distinguish from the trapped populations; although they do at times [Burrows, 1972] mingle with the trapped fluxes of similar energy, one usually finds the "cutoff" lying beyond the trapped distributions. Faneslow and Stone [1972] and Imhof et al. [1971] have measured the cutoffs of protons of 1.2 - 39 MeV and 1.4 - 46 MeV, respectively, at low altitudes. It is found that the cutoffs move to lower latitudes with increased activity; e.g., the 4-MeV-proton cutoff moved from 63.5° inv. lat. for $K_p = 1$, to 58° for $K_p = 4^-$ [Imhof et al. 1971]. The results of Faneslow and Stone and of Imhof et al., show the general energy dependence of trajectory analyses; the cutoffs, however, are generally 3 to 5 degrees lower than predicted.

Lanzerotti [1971] reports solar protons > 2 MeV on ATS 1. He reports a diurnal variation, fluxes higher at midnight than at noon, which correlates with measurements of proton-precipitation-induced gamma rays at balloon altitudes. Lanzerotti et al. [1971] report "drift-echoes" of azimuthally drifting solar protons at ATS 1 following impulsive acceleration at the time of the sudden commencement on November 20, 1968. They attribute the acceleration to third-invariant-violating radial diffusion.

The final question is where the particles enter. Lanzerotti [1972] discusses data from 14 different sources in the literature. Entry distances down the tail vary from 600 to 5000 R_E. He finds that the data are generally consistent with entry at ~ 1000 R_E. Fennell [1973] reports proton entry at 260 R_E for the HPL regions and 95 to 130 R_E for the LPL region. The results have been reinterpreted by Morfill and Scholer [1973b] as consistent with entry ~ 700 to 1000 R_E. They also interpret the available electron data as consistent with entry at 600 to 1000 R_E. Despite this general consistency, there are still many unanswered questions. Hopefully, in the near future, some clever theoretician will provide us with a quantitative model of the open magnetosphere to better explain the vast quantity of solar-particle magnetospheric-entry data that now exists.

Active Experiments

The earliest active experiments involved nuclear detonations such as the Argus experiments and the U.S.A. and Soviet high-altitude detonations in 1962. Although such detonations provided an abundance of information on electron transport and loss, they are not serious candidates for future work. There are three classes of experiments pertaining to energetic particles which hold promise for active experiments in the future: (1) the stimulation of wave-particle interactions through VLF transmission, (2) the stimulation of wave-particle interactions through cold-plasma injection, and (3) field-line tracing and wave-particle stimulation by accelerator-injected particles.

The most recent work in stimulating wave-particle interactions by VLF transmission is that of Helliwell and Katsufrakis [1974]. Signals of 1.5 to 16 kHz were transmitted from Siple Station (L = 4) and detected at the conjugate point, giving rise to wave growth and triggered emissions. They discuss modification of trapped electron populations, but the combined transmitter-satellite observations must wait for the future.

Brice [1971] has suggested the injection of barium clouds into the outer magnetospheric regions to stimulate the growth of both electron and proton cyclotron instabilities. Cornwall and Schulz [1971] and Cornwall [1972] have re-examined the suggestion and found that lithium is far more efficient for use in plasma-seeding experiments than barium. Liemohn [1974] has further developed the concepts of lithium-ion seeding experiments; and he provides specific calculations of the amplification of ion-cyclotron waves. Kivelson and Russell [1973] have considered the earlier ideas and point out that the Ogo-5 observations of detached plasma regions provide a naturally occurring analog which should be considered before proceeding to active experiments. They found that although wave growth occurred concurrent with the plasma clouds, the distribution of energetic electrons showed no measurable differences inside and outside the clouds. Proton measurements of the right energy were not available.

With the advent of the space shuttle, we can look forward to energetic-particle experiments from accelerator injection [Rosen, 1974]. Experiments so far have been largely feasibility experiments from rocket launches. The first experiment beamed the electrons downward to produce artificial aurorae [Hess et al., 1971]. Davis [1973] has reported preliminary results of electron injection along the field lines to produce aurorae at the conjugate point. French and Soviet scientists have planned a rocket-borne electron-gun experiment for 1975 [Gendrin, 1974b]; they plan particle-azimuthal-drift and wave-particle-interaction studies. The Minnesota group has initiated a fairly extensive undertaking, the Echo Program [Hendrickson et al., 1971]. The most complete experiment to date, Echo 1 [McEntire et al., 1974], resulted in 35- to 43-keV electrons being injected at L = 2.56. The electrons bounced off the top of the atmosphere at the conjugate point and were detected returning from one, two, and in one case three complete bounces from the Southern Hemisphere. The study of waves associated with the beam injection during the experiment is reported by Cartwright and Kellogg [1974]. Following this success, the Echo II experiment was launched from Fort Churchill. Although data taken about the same time from the low-altitude polar-orbiting Isis-II satellite indicated that the launch site was inside the 35-keV trapping boundary, clearly defined echoes were not obtained. The investigators are still in the process of analyzing their data but emphasize the need for rocket launches at lower latitudes where the magnetospheric processes, expected to be encountered by the probing electron beam, are less complicated. Unfortunately it will be the 1980's before such accelerator studies can be conducted on the space shuttle.

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