NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Memorandum 33-766

Energetic Particles of the Outer Regions of Planetary Magnetospheres

Bruce T. Tsurutani

Bruce E. Goldstein

Alexander Bratenahl

(NASA-CR-146582) ENERGETIC PARTICLES OF THE OUTER REGIONS OF PLANETARY MAGNETOSPHERES (Jet Propulsion Lab.) 18 p HC $3.50 CSCL 03B

N76-22137

Unclas

G3/93 21503

JET PROPULSION LABORATORY

CALIFORNIA INSTITUTE OF TECHNOLOGY

PASADENA, CALIFORNIA

March 1, 1976

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. 33-766	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle

ENERGETIC PARTICLES OF THE OUTER REGIONS OF PLANETARY MAGNETOSPHERES

5. Report Date

March 1, 1976

6. Performing Organization Code

7. Author(s) Bruce T. Tsurutani, Bruce E. Goldstein, Alexander Bratenahl

8. Performing Organization Report No.

9. Performing Organization Name and Address

JET PROPULSION LABORATORY
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91103

10. Work Unit No.

11. Contract or Grant No.
NAS 7-100

13. Type of Report and Period Covered

Technical Memorandum

12. Sponsoring Agency Name and Address

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C. 20546

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

High energy particles, with energies above those attainable by adiabatic or steady-state electric field acceleration, have been observed in and around the outer regions of planetary magnetospheres. Acceleration by large amplitude sporadic cross-tail electric fields over an order of magnitude greater than steady-state convection fields is proposed as a source of these particles. It is suggested that such explosive electric fields will occur intermittently in the vicinity of the tail neutral line in the expansive phases of substorms. Laboratory and satellite evidence are used to estimate this electric potential for substorms at earth; values of 500 kilovolts to 2 megavolts are calculated, in agreement with particle observations. It is further suggested that these particles, which have been accelerated in the night side magnetosphere, drift to the dayside on closed field lines, and under certain interplanetary conditions can escape to regions upstream of the bow shock.

17. Key Words (Selected by Author(s))	18. Distribution Statement
Space Sciences (General) Astrophysics Space Radiation	Unclassified -- Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	13	

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Memorandum 33-766

Energetic Particles of the Outer Regions of Planetary Magnetospheres

Bruce T. Tsurutani
Bruce E. Goldstein
Alexander Bratenahl

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

March 1, 1976

PREFACE

The work described in this report was performed by the Space Sciences Division of the Jet Propulsion Laboratory.

CONTENTS

FIGURE

ABSTRACT

High energy particles, with energies above those attainable by adiabatic or steady-state electric field acceleration, have been observed in and around the outer regions of planetary magnetospheres. Acceleration by large amplitude sporadic cross-tail electric fields over an order of magnitude greater than steady-state convection fields is proposed as a source of these particles. It is suggested that such explosive electric fields will occur intermittently in the vicinity of the tail neutral line in the expansive phases of substorms. Laboratory and satellite evidence are used to estimate this electric potential for substorms at earth; values of 500 kilovolts to 2 megavolts are calculated, in agreement with particle observations. It is further suggested that these particles, which have been accelerated in the night side magnetosphere, drift to the dayside on closed field lines, and under certain interplanetary conditions can escape to regions upstream of the bow shock.

ENERGETIC PARTICLES OF THE OUTER REGIONS
OF PLANETARY MAGNETOSPHERES

INTRODUCTION

Energization processes for the bulk of magnetospheric particles are well understood, at least for the earth. In the outer zone, convection electric fields coupled with the conservation of the first two adiabatic invariants lead to acceleration and energization of the magnetospheric plasma. In the inner zone, electrons and protons are energized by inward radial diffusion (Parker, 1960; Davis and Chang, 1962; Fälthammer, 1965; Birmingham et al., 1967); this process is caused by the violation of the third adiabatic invariant due to solar wind pressure fluctuations and fluctuating magnetospheric electric fields (Mozer and Manka, 1971). Cosmic ray albedo neutrons are an important source of energetic protons and low energy electrons for the earth's inner zone.

However, in the outer zone magnetosphere and tail, particles have been detected with energies above the $\sim$ 40 kev that can be ascribed to adiabatic and steady-state cross-tail electric accelerations. Konradi (1967) has observed 100-300 kev protons injected into the region L>8 in the nightside magnetosphere during substorms. The ATS-1 electron experiment (Parks et al., 1968; Arnoldy and Chan, 1969; Lezniak and Winckler, 1970) detected 50 to 150 kev electrons injected during substorms. Subsequent ATS-5 results (Bogott and Mozer, 1971; Tsurutani and Bogott, 1972) have substantiated these results for both protons and electrons in the energy range 30 to 300 kev.

Particles above 40 kev have also been seen in the tail. Electrons with energies greater than 45 kev were observed during substorms in plasma sheet expansions (Anderson et al., 1965; Meng and Anderson, 1971). Relativistic electrons, with $E \sim 400$ kev, have been detected near the neutral sheet (Murayama and Simpson, 1968; Retzler and Simpson, 1969). More recently, nearly completely stripped heavy ions with $E > 120$ kev/charge have been detected in the dusk side tail (Fan et al., 1975). These energetic particles cannot be explained by adiabatic compression or steady-state cross-tail acceleration.

This problem becomes even more serious when recent observations in the magnetosphere of Mercury are considered (Simpson, personal communication). Although the potential across the magnetotail of Mercury is only of the order of 25 kv, bursts of $\sim$ 300 kev electrons and $\sim$ 550 kev protons were detected in the tail of Mercury (Simpson et al., 1974), perhaps associated with substorms (Siscoe et al., 1975). As the solar wind magnetic field in the vicinity of Mercury is 20γ, and the maximum field observed at closest approach was only 98γ (Ness et al., 1974), adiabatic energization of particles by radial diffusion cannot explain such particles at any location in the Mercurian magnetosphere.

Similar difficulties arise at Jupiter. Particle experiments on Pioneers 10 and 11 detected electrons with energies up to 30 Mev and protons with energies up to 77 Mev in the outer portions of the magnetosphere (Trainor et al., 1974; Fillius and McIlwain, 1974; Van Allen et al., 1974; Chenette et al., 1974). Steady-state magnetospheric cross-tail potentials are only of the order of 500 kilovolts and are thus insufficient for acceleration to these energies. Such high energy particles exist in the inner magnetosphere; these particles presumably have been energized by radial diffusion processes (Jacques and Davis, 1972; Brice and McDonough, 1973; Stansberry and White, 1974). Escape of these particles to the outer magnetosphere is difficult because such a process must avoid magnetic decompression and particle energy reduction.

Clearly, some mechanism other than adiabatic acceleration must play an important role in energizing particles in outer magnetospheres. This problem has been recognized for some time (Lanzerotti, 1968, and others since then), yet the source of the high energy particles remains a mystery (Roederer and Hones, 1974, see last paragraph). It has been suggested (Sentman and Van Allen, 1975; Nishida, 1975) that trans-L shell diffusion at low altitudes without loss of energy could populate the outer magnetosphere (such theories do not explain the energetic particles convected in from the tail during substorms). Sarris et al. (1975) have recently proposed that acceleration of high energy particles occurs in double potential layers, or is due to plasma wave turbulence. As an alternative to these theories, we propose that the necessary acceleration is provided by the existence of large amplitude, sporadic, cross-tail electric fields over an order of magnitude larger than convection electric fields. Such fields could be generated during expansive phases of substorms in the tail reconnection region.

DAWN-DUSK SPORADIC ELECTRIC FIELDS IN THE VICINITY OF THE TAIL NEUTRAL LINE

In the current view of substorm processes, enhanced dayside field reconnection occurs during periods of southwardly directed interplanetary magnetic fields. The solar wind then drags the interconnected field lines into the geomagnetic tail leading to increased magnetic stress and a neutral line formation at distances of 10 to 15 R_e from earth (Atkinson, 1966; Nishida and Nagayama, 1973; Nishida and Hones, 1974). The field reconnection rate at this neutral line must, on the average, be equal to the dayside flux cutting rate. However, instantaneous reconnection rates may be more than an order of magnitude above average values. This is the phenomenon that we consider here.

Merging in the tail is controlled by local conditions at the neutral line. In our model sudden large resistivity increases (due to effects of plasma instabilities) occur in the vicinity of the neutral line during the expansive phases of substorms. Because the cross-tail current is controlled by the magnetic flux reversal across the neutral sheet, the cross-tail electric field must increase in response to the rise in resistivity. The time-dependent electric field measures the rate of transfer of tail lobe flux to the inner system of closed field lines; large electric fields imply rapid magnetic merging. In this picture, the merging in the tail is a pulselike process which generates electric fields 10 to 30 times larger than time-averaged fields.

This substorm model is suggested by a laboratory experiment, the Double Inverse Pinch Device (DIPD) (Bratenahl and Yeates, 1970; Baum et al., 1973; Baum and Bratenahl, 1974) and is supported by spacecraft observations and theoretical considerations. The DIPD experiment is specifically designed to investigate magnetic merging. The apparatus is a cylindrical plasma chamber which contains two conducting rods parallel to the cylinder axis; equal currents driven through the rods in the same direction produce a magnetic configuration that has a neutral line midway between and parallel to the rods. The magnetic field in a plane perpendicular to the axis has an x-point configuration. A detailed description is given in Bratenahl and Yeates (1970). As current on the rods is increased, substantial magnetic merging is prevented by plasma conductivity, and increasing magnetic fields result. Next, a sudden slight increase in "neutral sheet" conductivity occurs due to currents carried by runaway electrons accelerated by the "pre-explosion" electric field; this is immediately followed by a factor of 100 increase in the plasma resistance. Ion-acoustic turbulence is observed simultaneously with the onset of the resistance increase. The process is nothing less than an explosive release of magnetic energy; blast waves travel downstream from the neutral point and fast mode rarefaction waves propagate upstream from the neutral point to the rods. A detailed, quantitative, comparison between DIPD results and substorm processes is unjustified because of considerable physical differences (for the DIPD, collisions are important and the field geometry is less flattened).

Nonetheless, a striking analogy can be drawn between the DIPD results and substorm phenomenology. Eastwood (1974) shows that enhanced tail lobe flux causes a decrease of the B_z component of the neutral sheet field with a consequent increase in plasma sheet conductivity that slows the rate of magnetic merging. This conductivity increase is limited by the increase of the proton gyroradius to values that are comparable to the tail width. Acceleration of 40 kev protons across the tail is then expected to create resistive instabilities growing on a very short time scale. Other possible anomalous resistance mechanisms are discussed by Hamberger and Friedman (1968). Also, Scarf et al. (1974) observe $(n+1/2)\ f_c$ electrostatic waves near the neutral sheet during substorm periods. Large electric fields will then result from increased resistance. Typically, plasma turbulence prevents the bulk of the plasma distribution from being accelerated to large energies, but a runaway portion on the tail of the distribution function will be accelerated. Minimum B trapping (Speiser, 1967) will confine particles to the vicinity of the neutral merging line and allow such accelerated particles to acquire the full cross-tail potential difference. In fact, Sarris et al. (1975), have observed 10 to 30 second pulses of protons with energies up to 1.9 mev at 30 R_e from earth in the dusk side plasma sheet. Low energy particles are observed to arrive before high energy particles; this inverse dispersion could be explained by both the finite rise time for the electric field and the greater distance travelled across the tail by the more energetic particles.

Estimates of cross-tail electric fields can also be made independently of the numerous high energy particle observations. Plasma velocities and magnetic field magnitudes determine the electric field by the relationship $E = -V \times B$. A rarefaction wave resulting from sudden merging cannot propagate upstream (towards the tail lobes) with velocity larger than the fast mode wave speed. Theoretical studies of magnetic merging suggest the Alfvén speed (both fast mode and Alfvén speeds are of the same order of magnitude in the plasma sheet) for the maximum possible merging rate (Vasyliunas, 1975). Using $n \approx 1\ cm^{-3}$ and $B = 30\gamma$, the Alfvén speed, C_A, is 700 km/sec. The cross-tail potential, ϕ, is then determined by $\phi / L = E_y = C_A B$, and choosing $L = 20\ R_e$ results in $E_y = 20$ mv/m and $\phi = 1.9$ megavolts (this estimate is conservative as thinning of the plasma sheet during substorms may reduce densities when merging occurs). Such a cross-tail potential is consistent with spin modulated plasma fluxes (e.g., Hones et al., 1974, Fig. 6) observed at $X_{SM} = -18\ R_e$ in the plasma sheet during a substorm. On Aug. 31, 1970, from 1420 to 1440 UT, plasma velocities of as much as 200 km/sec in the solar magnetospheric z component are indicated (an alternative interpretation is that temporal variations within a satellite spin period produce apparent directed plasma fluxes). Estimating $E_y = -V_z B_x$, a B_x of 30γ implies a cross-tail potential of 550 kilovolts. These estimates can be compared to irregular convection electric fields of greater than 50 mv/m associated with plasma sheet electrons that have been observed by Gurnett and Frank (1973) at low altitudes over auroral field lines; they estimated polar cap potentials of about 240 kilovolts. The polar cap potential is a lower limit for the actual cross-tail fields as the large tail electric fields are due to dB/dt and are not curl-free.

Scaling the results of the DIPD experiment to the earth's magnetosphere also suggests large electric fields. On the basis of Faraday's law,

$$\phi = \frac{d}{dt} \oint \bar{B} \cdot \overline{ds}$$

Writing this equation in dimensional form, the following relation is obtained:

$$\phi_{tail} = \phi_{lab} \, (B_{tail}/B_{lab}) \, (L_{tail}/L_{lab})^2 \, (t_{lab}/t_{tail}).$$

Using the values ϕ_{lab} = 3000 volts, L_{lab} = 10 cm, $B_{lab} = 10^9$ γ, $t_{lab} = 10^{-6}$ sec, L_{tail} = 20 R_e, B_{tail} = 30 γ, and t_{tail} = 120 sec (time comparable with sudden arc brightening: Akasofu, 1964; Kisabeth and Rostoker, 1974), a cross-tail potential of 1.2 megavolts is predicted.

Assuming that large electric fields do occur, the proposed mechanism is capable of producing the observed particle fluxes. If the neutral line merging region is 1000 km by 10000 km by 30 R_e in volume, if the plasma density in the merging region is 1 cm^{-3}, if all particles in the merging region are accelerated to high energies within a 30 second period, and if the energetic particles are observed in a cross-sectional area 2 R_e by 10 R_e, then the integrated flux of high energy particles is 6 x 10^6 cm^{-2} sec^{-1}. Such fluxes are much larger than those actually observed; therefore the acceleration mechanism would not have to be extremely efficient. More detailed estimates of particle fluxes require consideration of magnetic field $\bar{v} \times \bar{B}$ forces, but, as the time-dependent magnetic and electric fields in the vicinity of the neutral line are not known, realistic calculations of particle fluxes are not yet possible.

SOME FURTHER POSSIBLE CONSEQUENCES OF SPORADIC E FIELDS

Energization of particles in the midnight-sector magnetosphere by impulsive electric fields may also be the source of energetic particles observed outside the magnetosphere (2 and 3 , Fig. 1). After energization near the nightside neutral line (1), some particles are injected onto midnight sector closed field lines (Axford, 1969; Roederer and Hones, 1974). Subsequent gradient and curvature drifts of these particles will populate the outer magnetosphere. Thus, the outer magnetosphere will be a reservoir for substorm accelerated high energy particles. Given certain interplanetary field conditions, these stored particles may escape to regions upstream of the bow shock ((2)).

Bursts of energetic E > 40 kev particles have been detected upstream of planetary bow shocks when the interplanetary magnetic field line passing through the spacecraft intercepted the shocks. Electrons (Fan et al., 1964; Anderson et al., 1965; Sarris et al., 1975) and protons (Lin et al., 1974; Sarris et al., 1975) have been detected upstream of the earth, and electrons of energies E ≃ 3-30 mev (Trainor et al., 1974; Chennette et al., 1974) have been detected upstream of Jupiter. As observations upstream of bow shocks by planetary-orbiting spacecraft are generally confined to the near-ecliptic plane, particles that propagate upstream to spacecraft detectors must travel along field lines that are nearly parallel to the ecliptic plane. However, because the magnetic dipoles of the Earth, Jupiter, and Mercury and the dayside magnetospheric fields are aligned almost normal to the ecliptic, and because strong dayside field line merging will occur when the interplanetary field is antiparallel to the planetary field (Gonzalez and Mozer, 1974), average or low geomagnetic activity would be expected during the periods most favorable for observation of upstream particles. Therefore, the observed lack of correlation between K_p and upstream particle detection (Anderson, 1968; Lin et al., 1974) is consistent with a substorm origin of upstream particles.

In contrast, high flux cutting rates and high geomagnetic activity should occur when the interplanetary magnetic field is parallel to the planetary dipole direction (Fig. 1 (3)). With large erosion of dayside magnetic flux, large fluxes of > 40 kev electrons and protons populating those field lines would be expected to escape from the magnetosphere with a flow perpendicular to the ecliptic plane. Observational testing of this hypothesis has not been done yet due to orbital limitation of existing satellites.

COMMENTS

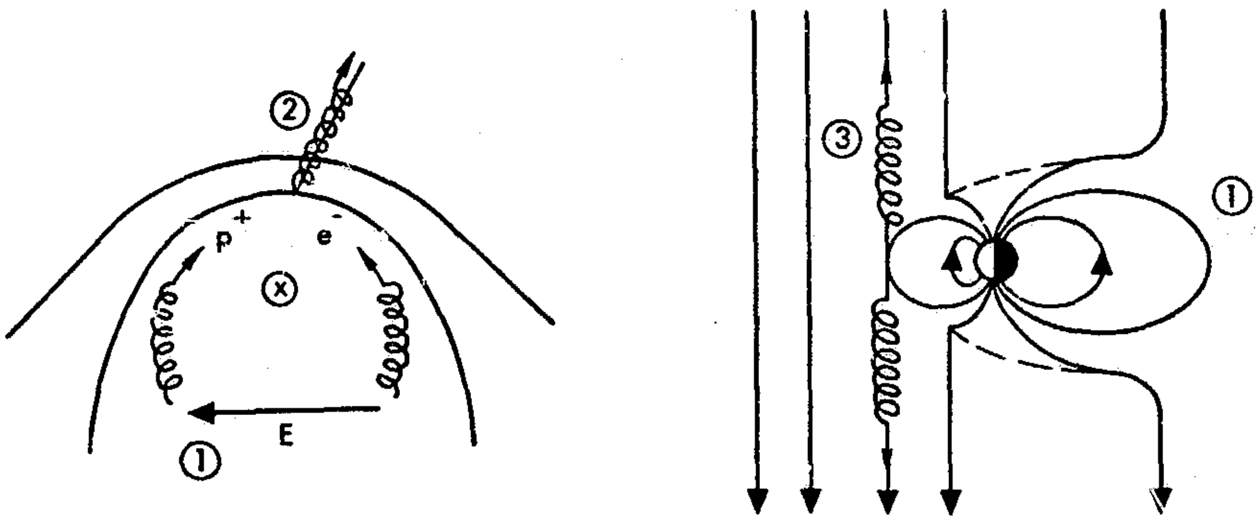
The possible consequences of sporadic field merging discussed in this note are clearly speculative. We present these ideas in hope of stimulating space experiments, laboratory studies, and theoretical investigations aimed at a better understanding of transient magnetic merging. It is anticipated that impulsive merging processes will have important implications for magnetospheric physics.

ACKNOWLEDGEMENTS

The authors would like to thank M. Neugebauer, E. J. Smith, J. Luthey, H. Wahlquist and D. Clay for helpful suggestions for this paper. This paper represents one aspect of research conducted by the Jet Propulsion Laboratory under Contract No. NAS7-100 sponsored by the National Aeronautics and Space Administration.

FIGURE CAPTION

Figure 1: Particle acceleration by sporadic cross-tail electric fields occurs at (1) during the expansion phase of a substorm. Gradient and curvature drifts of accelerated particles populate the outer regions of the magnetosphere. Interplanetary magnetic field connection at the nose of the magnetosphere allows escape of particles to regions upstream of the bow shock (2). Strong southward interplanetary magnetic fields will allow particle escape out of the ecliptic plane (3).



1a 1b

REFERENCES

Akasofu, S-I., The development of the auroral substorm, Planet Space Sci., 12, 273, 1964.

Anderson, K. A., Energetic electrons of terrestrial origin upstream in the solar wind, J. Geophys. Res., 73, 2387, 1968.

Anderson, K. A., H. K. Harris and R. J. Paoli, Energetic electron fluxes in and beyond the earth's outer magnetosphere, J. Geophys. Res., 70, 1039, 1965.

Arnoldy, R. L. and K. W. Chan, Particle substorms observed at the geostationary orbit, J. Geophys. Res., 74, 5019, 1969.

Atkinson, G., A theory of polar substorms, J. Geophys. Res., 71, 5157, 1966.

Axford, W. I., Magnetospheric convection, Rev. Geophys., 1, 421, 1969.

Baum, P. J., A. Bratenahl and R. S. White, Experimental study of the reconnection process, Radio Science, 8, 917, 1973.

Baum, P. J. and A. Bratenahl, Mass motion and heating in a magnetic neutral point system, J. Plasma Phys., 11, 93, 1974.

Birmingham, T. J., T. G. Northrup, and C. G. Fälthammer, Charged particle diffusion by violation of the third adiabatic invariant, Phys. Fluids, 10, 2389, 1967.

Bogott, F. H. and F. S. Mozer, Equatorial proton and electron angular distributions in the loss cone and at large angles, J. Geophys. Res., 76, 6790, 1971.

Bratenahl, A. and C. M. Yeates, Experimental studies of magnetic flux transfer at the hyperbolic neutral point, Phys. Fluids, 13, 2696, 1970.

Brice, N. and T. R. McDonough, Jupiter's radiation belts, Icarus, 18, 206, 1973.

Chenette, D. L., T. F. Conlon, and J. A. Simpson, Bursts of relativistic electrons from Jupiter observed in interplanetary space with the time variation of the planetary rotation period, J. Geophys. Res., 79, 3551, 1974.

Davis, L., Jr. and D. B. Chang, On the effect of geomagnetic fluctuations on trapped particles, J. Geophys. Res., 67, 2169, 1962.

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

Eastwood, J. W., The warm current sheet model, and its implications on the temporal behavior of the geomagnetic tail, Planet. Space Sci., 22, 1641, 1974.

Fälthammer, C. G., Effects of time-dependent electric fields on geomagnetically trapped radiation, J. Geophys. Res., 70, 2503, 1965.

Fan, C. Y., G. Gloecker and J. A. Simpson, Evidence for >30-keV electrons accelerated in the shock transition region beyond the Earth's magnetospheric boundary, Phys. Rev. Letts., 13, 149 1964.

Fan, C. Y., G. Gloeckler, and D. Hovestadt, Energy spectra and charge states of H, He, and heavy ions observed in the Earth's magnetosheath and magnetotail, Phys. Rev. Letts., 34, 495, 1975.

Fillius, R. W. and C. E. McIlwain, Measurements of the Jovian radiation belts, J. Geophys. Res., 79, 3589, 1974.

Gonzalez, W. D. and F. S. Mozer, A quantitative model for the potential resulting from reconnection with an arbitrary interplanetary magnetic field. J. Geophys. Res., 79, 4186, 1974.

Gurnett, D. A. and L. A. Frank, Observed relationships between electric fields and auroral particle precipitation, J. Geophys. Res., 78, 145, 1973.

Hamberger, S. M. and M. Friedman, Electrical conductivity of a highly turbulent plasma, Phys. Rev. Letts. 21, 674, 1968.

Hones, E. W., Jr., A. T. Y. Lui, S. J. Bame and S. Singer, Prolonged tailward flow of plasma in the thinned plasma sheet observed at $r = 18\ R_E$ during substorms, J. Geophys. Res., 79, 1385, 1974.

Jacques, S. A. and L. Davis Jr., Diffusion models for Jupiter's radiation belt, California Inst. of Technology Technical Report, 1972.

Lanzerotti, L. J., Comparison of the electron response in the magnetosphere at L=5 with the solar wind during the April 17-18, 1965, magnetic storm, J. Geophys. Res., 73, 438, 1968.

Kisabeth, J. L., and G. Rostoker, The expansive phase of magnetospheric substorms 1. Development of the auroral electrojets and auroral arc configuration during a substorm, J. Geophys. Res., 79, 972, 1974.

Konradi, A., Proton events in the magnetosphere associated with magnetic bays, J. Geophys. Res., 72, 3829, 1967.

Lezniak, T. W. and J. R. Winckler, Experimental study of magnetospheric motions of energetic electrons during substorm, J. Geophys. Res., 75, 7075, 1970.

Lin, R. P., C.-I. Meng and K. A. Anderson, 30 to 100 keV protons upstream from the Earth's bow shock, J. Geophys. Res., 79, 489, 1974.

Meng, C.-I., and K.A. Anderson, Energetic electrons in the plasma sheet out to 40 R_E, J. Geophys. Res., 76, 873, 1971.

Mozer, F. S. and R. H. Manka, Magnetospheric electric field properties deduced from simultaneous ballon flights, J. Geophys. Res., 76, 1697, 1971.

Murayama, T. and J. A. Simpson, Electrons within the neutral sheet of the magnetospheric tail, J. Geophys. Res., 73, 891, 1968.

Ness, N. F., K. W. Behannon, R. P. Lepping, Y. C. Whang and K. H. Schatten, Magnetic field observation near Mercury: Preliminary results from Mariner 10, Science, 185, 151, 1974.

Nishida, A., Outward diffusion of energetic particles from the Jovian radiation belt, University of Tokyo preprint, 1975.

Nishida, A., and E. W. Hones, Jr., Association of plasma sheet thinning with neutral line formation in the magnetotail, J. Geophys. Res., 79, 535, 1974.

Nishida, A., and N. Nagayama, Synoptic survey for the neutral line in the magnetotail during the substorm expansion phase, J. Geophys. Res., 78, 3782, 1973.

Parker, E. N., Geomagnetic fluctuations and the form of the outer zone of the Van Allen radiation belt, J. Geophys. Res., 65, 3117, 1960.

Parks, G. K., R. L. Arnoldy, T. N. Lezniak and J. R. Winckler, Correlated effects of energetic electrons at the 6.6 R_E equator and the auroral zone during magnetospheric substorms, Radio Sci., 3, 715, 1968.

Retzler, J. and J. A. Simpson, Relativistic electrons confined within the neutral sheet of the geomagnetic tail, J. Geophys. Res., 74, 2149, 1969.

Roederer, J. G. and E. W. Hones, Jr., Motion of magnetospheric particle clouds in a time-dependent electric field model, J. Geophys. Res., 79, 1432, 1974.

Sarris, E. T., S. M. Krimigis and T. P. Armstrong, Observations of magnetospheric bursts of high energy protons and electrons at 35 R_E with IMP-7 Johns Hopkins Univ., preprint 1975.

Scarf, F. L., L. A. Frank, K.L. Ackerson, and R. P. Lepping, Plasma wave turbulence at distant crossing of the plasma sheet boundaries and at the neutral sheet, Geophys. Res. Letts., 1, 189, 1974.

Sentman, D. D., and J. A. Van Allen, Recirculation of energetic particles in Jupiter's magnetosphere, Geophys. Res. Letts., 2, 465, 1975.

Simpson, J. A., J. H. Eraker, J. E. Lamport and P. H. Walpole, Electrons and protons accelerated in Mercury's magnetic field, Science, 185, 160, 1974.

Siscoe, G. L., N. F. Ness and C. M. Yeates, Substorms on Mercury?, J. Geophys. Res., 80, 4359, 1975.

Speiser, T. W., Particle trajectories in model current sheets, 2. Applications to auroras using a geomagnetic tail model, J. Geophys. Res., 72, 3919, 1967.

Stansberry, K. G., and R. S. White, Jupiter's radiation belts, J. Geophys. Res., 79, 2331, 1974.

Trainor, J. H., F. B. McDonald, B. J. Teegarden, W. R. Webber, and E. C. Roelof, Energetic particles in the Jovian magnetosphere, J. Geophys. Res., 79, 3600, 1974.

Tsurutani, B. and F. Bogott, Onset of magnetospheric substorms, J. Geophys. Res., 77, 4677, 1972.

Van Allen, J. A., D. N. Baker, B. A. Randall and D. D. Sentman, The magnetosphere of Jupiter as observed with Pioneer 10, 1. Instrument and principal findings, J. Geophys. Res., 79, 3559, 1974.

Vasyliunas, V. M., Theoretical models of magnetic field line merging, 1, Rev. Geophys. and Space Phys., 13, 303, 1975.

NASA—JPL—Coml., L.A., Calif.