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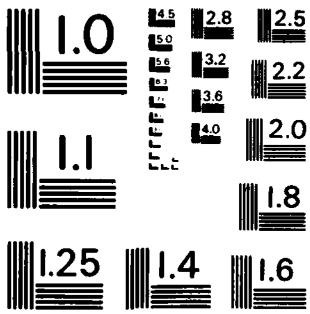

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FINAL REPORT
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University of California, Los Angeles

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- TECHNICAL OBJECTIVE: (U) THE IONOSPHERIC DISTURBANCES ASSOCIATED WITH GEOMAGNETIC STORMS DEGRADE OR DISRUPT NAVAL COMMUNICATIONS, NAVIGATION, AND SURVEILLANCE SYSTEMS. THE OBJECTIVE OF THIS PROGRAM IS TO DEVELOP AN UNDERSTANDING OF THE TRIGGERING MECHANISM, EVOLUTION, LOCATION, EXTENT AND MAGNITUDE OF GEOMAGNETIC STORMS REQUIRED TO PREDICT THEIR OCCURRENCE AND EFFECTS ON NAVAL ELECTROMAGNETIC SYSTEMS.
- APPROACH: (U) GROUND AND SATELLITE MAGNETOMETER DATA ARE USED TO MONITOR MICROPULSATIONS AND ELECTRIC CURRENTS IN THE MAGNETOSPHERE AND IONOSPHERE DURING MAGNETIC SUBSTORMS. THE FORMATION OF PARTIAL RING CURRENTS AND ITS RELATIONSHIP TO SOLAR WIND PARAMETERS AND THE RELATIONSHIP BETWEEN MAGNETIC MICROPULSATIONS AND TRIGGERING SUBSTORMS

IS INVESTIGATED.
- PROGRESS: (U) IT HAS BEEN FOUND THAT ABOUT HALF OF THE MAGNETIC FLUCTUATIONS ASSOCIATED WITH GEOMAGNETIC STORMS IS DIRECTLY DRIVEN BY THE SOLAR WIND. THE MAGNETOSPHERE ACTS LIKE A RAYLEIGH FILTER TOSOLAR WIND FLUCTUATIONS. ITS PEAK RESPONSE COMES 40 MINUTES AFTER AN IMPULSE. (C. T. CLAUER AND R.L. MCPHERRON, 'THE RELATIVE IMPORTANCE OF THE INTERPLANETARY MAGNETIC FIELD AND MAGNETOSPHERIC SUBSTORMS ON PARTIAL RING CURRENT DEVELOPMENT', J. GEOPHYS RES 85, 6747, 1980).
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CONTENTS

1. INTRODUCTION

The Space Science Group of the Institute of Geophysics and Planetary Physics at the University of California, Los Angeles is primarily an experimental group dedicated to the measurement, interpretation, and explanation of observations of magnetic fields. The primary activity of the Space Science Group is the study of magnetic field measurements made by fluxgate magnetometers on spacecraft in the magnetosphere, in the solar wind and in space around other planets. Since magnetic fields permeate all space plasmas and control their behavior, study of magnetic field measurements has involved the Space Science Group in a wide variety of subjects. These topics include: the solar wind and its internal structure; the solar wind interaction with planetary bodies; structure and dynamics of planetary magnetic fields; quantitative models of planetary fields and current systems; origins of magnetic activity; sources and properties of Ultra Low Frequency Waves (ULF), and effects of tectonic stress on rock magnetism.

The faculty and research staff of the Space Science Group have collectively published more than 400 papers during 15 years of active involvement in the space program. A significant number of these publications have been supported by the Office of Naval Research. ONR sponsored research has covered several subtopics within the general area of solar-terrestrial physics. These include: solar wind controlled dayside magnetic pulsations; substorm associated magnetic pulsations; magnetic storms, and magnetospheric substorms. The primary goal of this research is to understand the sequence of physical processes through which energy is transferred from the solar wind to the magnetosphere, and ultimately to the earth's atmosphere. Our approach to this problem is in two parts. One part is the study of magnetic perturbations, within the magnetosphere and on the ground, caused by changes in the solar wind. These studies provide information primarily about the electrical current systems that link the solar wind, magnetosphere, and ionosphere. The second part is the study of ultra low frequency (ULF) waves. These studies provide detailed information concerning the state of the magnetospheric plasma, as well as that of the solar wind. An underlying theme in this work is the development of quantitative methods for remotely sensing the state of the magnetosphere and solar wind from the earth's surface. An integral part of our work is the development of techniques for the management and analysis of the large digital data base necessary to carry out our work.

Although our work under ONR sponsorship is continuing, we are preparing a final report because of a change in contract number. To do this we have assembled a complete bibliography of all publications to date. This bibliography has been subdivided into four sections corresponding to our four main areas of research. In subsequent sections we highlight major results obtained in this work.

2. STUDIES OF ULF WAVES

ULF waves are observed continuously by magnetometers on spacecraft in the magnetosphere and by magnetometers on the ground as pulsations in the magnetic field with small amplitude (.1-10 nT) and long period (1-1000 sec). Their waveforms have been classified arbitrarily as Pc (pulsations continuous) or Pi (pulsations irregular) depending on whether they are quasi-sinusoidal or not. Mechanisms for generating ULF waves include externally excited resonances of field lines, surface waves on boundary surfaces, and plasma instabilities. The characteristics of the waves observed *in situ* depend on the properties of the ambient plasma and the details of the generation mechanism. When observed on the ground their properties are modified by propagation effects. Theoretical models of the generation mechanisms in conjunction with observations provide a means for remotely sensing the properties of space plasmas.

2.1 SUBSTORM ASSOCIATED WAVES

Our work on substorm associated waves has been concerned with three subtypes of ULF waves: Pi 2, Pc 1, and Pc 5. Pi 2 pulsations (Pulsations Irregular of 45-150 sec period) are a night time phenomenon associated with the onset or intensification of the expansion phase of substorms. For a number of years the beginning of a Pi 2 burst has been used as a timing mark in the study of substorm morphology. At the present time there is no accepted explanation for their generation. It has been suggested that they are a transient disturbance associated with the diversion of the tail current along field lines to the westward electrojet. Our work with Pi 2 has emphasized the characteristics of these waves as observed in space by synchronous spacecraft. In papers (10) and (35) we were the first to point out the existence of such waves in space. In particular, we noted that Pi 2 are frequently accompanied by high frequency "riders" which are also seen on the ground near the satellite conjugate footprint. We also noted that typically more than one Pi 2 burst occurs in a single substorm, suggesting that substorms have more than one onset. In paper (40) we did a more statistical study of the properties of Pi 2 at synchronous orbit and found that the events can be divided into three types. The first is a superposition of a 100-second oscillation and a large-amplitude, higher frequency Pi 1 activity. The second is a 100-second wave unaccompanied by Pi 1. Both of these types have a significant compressional component. The third type is a pure transverse wave in the azimuthal component. All types of Pi 2 occur simultaneously with Pi 2 on the ground and are most probable around 2100 LT. An examination of Pi 2 polarization shows that the initial perturbation is in the same direction as that caused by field aligned currents connected to the westward electrojet. These results were used in paper (33) to suggest that the mechanism responsible for the pulsations was a sudden change in magnetospheric convection transmitted to the ionosphere by an Alfven wave. Resonant properties of the field line on which the Pi 2 wave travels probably control the wave period.

Another type of substorm wave which we have studied under ONR sponsorship is Pc 1 (Pulsations Continuous of 10 to 0.2 sec period). In our initial work, papers (26) and (27) we were the first to report these waves in space. In this work we established clearly that the subtype known as IPDP is seen simultaneously on the ground and in space, but that the identifying characteristic of a gradual decrease in frequency seen on the ground is not observed in space. We concluded that the waves are generated by the cyclotron instability of ring current protons injected by substorms that drift inward to regions of higher proton gyrofrequency. In recent work, paper (47), we have used data from a more sensitive instrument on the synchronous spacecraft ATS 6 to identify a second class of Pc 1. These waves tend to occur earlier in the day than IPDP, near local noon, and are linearly polarized. Also these waves appear at harmonics of the helium cyclotron frequency. A careful study of the spectra of the Pc 1 pulsations suggests that it is possible to determine the relative composition of helium and hydrogen in the ambient plasma from wave observations alone. Typically we find this is less than 7%.

A third type of substorm associated wave that we are studying is storm-time Pc 5 (150-500 sec period). In paper (49) we have used data from a pair of spacecraft in eccentric orbit to observe the properties of these waves at the dusk meridian. We have found for this case that waves were present continuously from the magnetopause to just inside the plasmapause. We find, in addition, that the most monochromatic waves were seen on the plasmapause and appear to be a consequence of a resonant interaction between energetic protons and the waves, but controlled by the properties of standing waves on the field lines through the spacecraft.

Two review papers covering the above work have also been written. Paper (19) summarized early results obtained using ATS 1 data, and paper (42) summarized results obtained with data from ATS 6. A bibliography of substorm associated pulsation work is presented in Table 1.

TABLE 1

ONR Publications Related to Substorm Associated Pulsations

10. Arthur, C.W. and R.L. McPherron, A preliminary study of simultaneous observations of substorm-associated Pi 2 micropulsations and their high-frequency enhancement, UCLA, IGPP Publication No. 1266-43, 1974.

19. Coleman, P.J., Jr. and R.L. McPherron, Substorm observations of magnetic perturbations and ULF waves at synchronous orbit by ATS-1 and ATS-6, The Scientific Satellite Program During the International Magnetospheric Study, edited by K. Knott and B. Battrick, D. Reidel Publ. Co., 345-364, 1976.

26. Bossen, M., R.L. McPherron, and C.T. Russell, A statistical study of Pc 1 magnetic pulsations at synchronous orbit, J. Geophys. Res., 81 (34), 6083, 1976.

27. Bossen, M., R.L. McPherron, and C.T. Russell, Simultaneous Pc 1 observations by the synchronous satellite ATS-1 and ground stations: Implications concerning IPDP generation mechanisms, J. Atmos. Terrest. Phys., 38, 1157-1167, 1976.

33. Southwood, D.J. and W.F. Stuart, Pulsations at the substorm onset, in Dynamics of the Magnetosphere, edited by S.-I. Akasofu, D. Reidel, Dordrecht, Holland, 341-356, 1980.

35. Arthur, C.W. and R.L. McPherron, Simultaneous ground-satellite observations of Pi 2 magnetic pulsations and their high-frequency enhancement, Planet. Space Sci., 28, 875-880, 1980.

40. Sakurai, T. and R.L. McPherron, Satellite observations of Pi 2 activity at synchronous orbit, submitted to JGR, J. Geophys. Res., December, 1981.

42. McPherron, R.L., Substorm-associated micropulsations at synchronous orbit, J. Geomag. Geoelectr., 32, Supp. II, SII 57-73, 1980.

45. Fraser, B.J., and R.L. McPherron, Pc 1-2 magnetic pulsation spectra and heavy ion effects at synchronous orbit: ATS 6 results, J. Geophys. Res., 87(A6), 4560-4566, 1982.

49. Greenstadt, E.W., R.L. McPherron, M. Hoppe, R.R. Anderson, and F.L. Scarf, A storm-time, Pc 5 event observed in the outer magnetosphere by ISEE 1 and 2: Wave Properties, to be submitted to J. Geophys. Res., January, 1983.

2.2 SOLAR WIND ASSOCIATED PULSATIONS

It has been established from ground observations that some continuous pulsations observed during daylight hours are correlated with the solar wind. These observations have been interpreted as supporting the theory of externally driven field-line resonance. Since many of the ground observations have been obtained at latitudes of field lines passing through synchronous orbit, it should be expected that pulsations at synchronous orbit would also exhibit a solar wind correlation. Our study of solar wind associated pulsations was initiated to determine if this were true. On the ground, waves of 15-45 sec period (Pc 3) are best correlated with the solar wind, so we began with a study of similar waves at synchronous orbit.

Paper (39) is an examination using a binary index of the factors affecting Pc 3 occurrence at synchronous orbit. This index was defined as zero, or one depending on the presence or absence of a spectral peak in the Pc 3 band. Using this index we established that Pc 3 pulsations at synchronous orbit occur only during daylight hours, with maximum probability at 0900 LT. Their probability of occurrence increases with either an increase in solar wind velocity or a decrease in the angle of the interplanetary magnetic field with respect to the earth-sun line. Also, because of the solar wind velocity dependence, Pc 3 pulsations are closely correlated with solar wind stream structure. A discussion of the implications of these and other results is given in paper (41). It is suggested that the observations are consistent with at least two mechanisms of external excitation, and possibly with both mechanisms acting jointly. One mechanism is the Kelvin-Helmholtz instability, which generates surface waves on the magnetopause which might couple to resonant field lines. The second mechanism is bow shock generated magnetosheath turbulence which may be transmitted through the magnetopause to drive resonant field lines. Alternatively, it is possible that magnetosheath turbulence is a source of noise amplified by the K-H instability which then couples to a resonance.

Power spectra of Pc 3 pulsations at synchronous orbit often show multiple peaks within the band. Close examination reveals that these peaks are harmonically related, with the separation of successive peaks corresponding to the fundamental frequency of resonance. This discovery of "harmonic events" is described in paper (47) and is used to determine parameters of a simple model of plasma distribution along field lines. Typical observations from ATS 6, for which the fundamental frequency decreases from 14 mHz in the morning to 10 mHz in the afternoon, imply that the equatorial mass density at synchronous orbit increases from 3 to 8 hydrogen masses per cubic cm throughout the day side.

A variation of resonant frequency with local time at synchronous orbit suggests that adjacent regions of the magnetosphere are not closely coupled. In paper (53) we utilized data from three synchronous spacecraft to demonstrate that different locations are simultaneously resonant with different frequencies. Only in the morning hours, when the observed frequency is relatively independent of local time, are observations between different spacecraft coherent. In a few cases of this type it is found that the spacecraft are probably separated by several wavelengths for which the azimuthal wave number is less than 10.

The method of indirect sensing of mass density developed in this research provides a means for monitoring the equatorial mass density at synchronous orbit as a function of geophysical activity. As a first step toward realizing this goal, we have calculated dynamic spectra for every day in the first 15 months of operation of ATS 6. The techniques used for creating these spectra, and microfiche copies of them, are reported in paper (52). Publications related to solar wind associated pulsations are listed on the following page.

TABLE 2

ONR Publications related to Pc 3 Magnetic Pulsations

39. Takahashi, K., R.L. McPherron, E.W. Greenstadt, and C.W. Arthur, Factors controlling the occurrence of Pc 3 magnetic pulsations at synchronous orbit, J. Geophys. Res., 86(A7), 5472-5484, 1981.

41. Greenstadt, E.W., R.L. McPherron, and K. Takahashi, Solar wind control of daytime, midperiod geomagnetic pulsations, J. Geomag. Geoelectr., 32, Suppl. II, SII 89-110, 1980.

47. Takahashi, K., and R.L. McPherron, Harmonic structure of Pc 3-4 pulsations, J. Geophys. Res., 87(A3), 1504-1516, 1982.

52. Takahashi, K., and R.L. McPherron, Dynamic spectral analysis of magnetic pulsation, *IGPP Publication* No. 2350, July 26, 1982.

53. Takahashi, K., R.L. McPherron, and W.J. Hughes, Multi-spacecraft observations of Pc 3-4 pulsations, IGPP Publication No. 2351, July 26, 1982.

3. STUDIES OF MAGNETIC STORMS

One of the outstanding problems of solar-terrestrial physics has been determining the mechanisms responsible for the storm time ring current. For many years it has been thought that this was a result of a succession of magnetospheric substorms, each of which injected particles near midnight. These particles were expected to drift towards dawn and dusk forming a partial ring current centered near midnight. Because drifting electrons are lost rapidly by precipitation it was suggested that the center of the partial ring current would shift towards dusk. As time progressed the long-lived protons drift completely around the earth, forming a symmetric ring current. Eventually, charge exchange near the atmosphere and ion cyclotron waves near the equator cause the ring current to decay.

Our work performed under ONR sponsorship casts doubts on some aspects of the foregoing model. As summarized below, we suggest ring current injection, and the formation of the partial ring current, are more closely related to the solar wind than to substorms.

3.1 RING CURRENT STUDIES

In paper (4) we compared high time resolution plots of the Dst index with plots of solar wind parameters during weak to moderate storm activity. We found that the Dst index appears to decrease more smoothly than expected on a basis of the episodic substorm injection model. Furthermore, we showed that the decrease is associated closely with a southward interplanetary magnetic field (IMF). Based on this result we undertook a study that utilized a new physical model of storm development. This model assumed the ring current grows by magnetospheric convection driven by the solar wind and decays by particle precipitation. Using a Dst index corrected for solar wind dynamic pressure we were able to estimate the ring current source function which has the form of a half-wave rectifier as discussed in paper (16). Using this source function and estimates of the decay time constant we were able in paper (17) to predict quite closely the time development of the Dst index without knowledge of substorm activity.

3.2 PARTIAL RING CURRENT STUDIES

More recently we have considered the question of the cause of the midlatitude asymmetry in the Dst index. Observationally this asymmetry is manifested as a storm-time disturbance that is larger near dusk than near dawn. In paper (30) we noted that the magnitude of this disturbance is correlated more closely with the integral of the solar wind electric field than the integral of the AL index (a measure of substorm activity). Also, we noted that the growth and decay of the asymmetry follow, with a very short delay, the southward and northward turning of the IMF. In paper (34) we developed these ideas and concluded that that it should be possible to use midlatitude asymmetry to monitor the strength of the solar wind electric field. Paper (38) completed this work with a statistical study which concluded that the partial ring current is driven by the solar wind rather than substorm expansions.

Recently we have approached the problem of solar wind control of geomagnetic activity using the technique of linear prediction filters. In this technique historical records are used to calculate an empirical transfer function relating an input and output time series. Then, by convolving the filter with an arbitrary input time series, a prediction of the output time series is obtained. In a paper just accepted for publication (Clauer, et al, 1983) we applied this technique to midlatitude asymmetry. We found that approximately 41% of the variance in the ASYM index can be predicted by the solar wind alone. Following a recent suggestion by Siscoe we attribute the predictable portion of the index to magnetic perturbations caused by field aligned currents driven by the solar wind. We also found that an additional 15% of the variance of the ASYM index is predictable by the AL index. This suggests to us that the solar wind is the primary cause of midlatitude asymmetry, but that substorm expansions play a secondary role.

Papers related to magnetic storm activity are listed in Table 3.

TABLE 3

ONR Publications Relating to Magnetic Storms

4. Russell, C.T., R.L. McPherron, and R.E. Burton, On the cause of geomagnetic storms, J. Geophys. Res., 79(7), 1105-1109, 1974.

16. Burton, R.K., R.L. McPherron, and C.T. Russell, The terrestrial magnetosphere: A half-wave rectifier of the interplanetary electric field, Science, 189, 717-718, 1975.

17. Burton, R.K., R.L. McPherron, and C.T. Russell, An empirical relationship between interplanetary conditions and Dst, J. Geophys. Res., 80(31), 4204-4214, 1975.

30. Clauer, C.R., and R.L. McPherron, On the relationship of the partial ring current to substorms and the interplanetary magnetic field, J. Geomag. Geoelectr., 30, 195-196, 1978.

34. Clauer, C.R. and R.L. McPherron, Predicting partial ring current development, Proceedings of the International Solar-Terrestrial Predictions Workshop, Boulder, Colorado, Volume 4, B44-B58, March, 1980.

38. Clauer, C.R. and R.L. McPherron, The relative importance of the interplanetary electric field and magnetospheric substorms on partial ring current development, J. Geophys. Res., 85(A12), 6747-6759, 1980.

4. STUDIES OF MAGNETOSPHERIC SUBSTORMS

A major fraction of our ONR sponsored work has been devoted to the subject of magnetospheric substorms. Since the beginning of our ONR support in 1972 we have been concerned primarily with establishing a phenomenological model which characterizes the changes in the earth's magnetic field during substorms. The main conclusion of this work is that the solar wind controls substorm activity through the processes of magnetic field merging on the day side and magnetic reconnection on the night side.

The characteristics of the magnetic field within the earth's tail have been described in a series of publications. In paper (2) we used a case history approach to show that the field increases prior to expansion onset and decreases afterwards. Paper (3) provided additional examples of this behavior and related these changes to effects seen in ground magnetograms. A statistical study of approximately 20 tail events was described in paper (6). This work noted that statistically the IMF appears to turn northward at about the time of major expansion onsets. An automated procedure for determining substorm onsets using digital magnetograms was developed in paper (11). Conclusions based on approximately 2000 onsets determined by this method were presented in (20). It was found that the properties of the tail field reported earlier using only a few events were characteristic of this large set of substorm expansions. In paper (21) we performed another case history study that verified the result of the statistical study that many major substorm expansions are triggered by northward turnings of the IMF. Paper (15) demonstrated that storm sudden commencements may also trigger expansion onset provided the tail is in an excited state as a result of a preceding interval of southward IMF. Paper

(43) reported the first simultaneous satellite particle and field observations of field aligned currents on the boundary of the plasma sheet as it expands during the recovery phase of substorms.

In a related set of papers we used multiple spacecraft observations to study the behavior of particles and fields simultaneously at several locations in the tail. In paper (13) we demonstrated that the substorm expansion is radially localized on the midnight meridian. Close to the earth the plasma sheet thins prior to expansion onset and expands afterwards. Farther from the earth the plasma sheet thins only after the expansion onset and expands later during the recovery phase of the substorm. Paper (14) studied the expansion of the plasma sheet, concluding that it is the consequence of rapid tailward motion of a near-earth neutral line formed during the expansion phase. The projection of this motion on the auroral ionosphere is observed as a poleward leap of auroral activity. Finally, paper (18) studied substorm activity during prolonged intervals of southward field. It shows that at such times the magnetosphere appears to enter a state of enhanced convection, which we referred to as a convection bay because of its effects in the auroral zone.

An examination of magnetic field changes at synchronous orbit during substorms is reported in papers (25) and (46). The first of these noted that a persistent feature of substorms at synchronous orbit is the development of azimuthal perturbations caused by field-aligned currents. The magnitude of these effects is seasonally dependent as a consequence of changes in the plane of magnetic symmetry produced by changes in the orientation of the dipole with respect to the earth-sun line. Paper (46) showed very clearly that the synchronous field becomes tail-like prior to expansion onset and more dipolar afterwards. Furthermore, it showed that this dipolarization is associated with particle injection.

Substorm effects seen in ground magnetic data have been the subject of another line of research. Paper (7) described a technique for mapping midlatitude magnetic disturbance and applied it to a number of substorms. The paper illustrated how such data can be used to determine the location of field-aligned currents connected to the westward electrojet during substorm expansion. Paper (8) demonstrated that these effects are highly variable and, contrary to common opinion, the substorm can be centered at local times other than midnight. Paper (9) described a more quantitative technique using inverse methods for determining the properties of such currents. In papers (30), (36) and (38) we examined the relationship of the midlatitude asymmetry to substorms and concluded that asymmetry is more likely to be caused by currents connected to the solar wind than to the tail.

An interesting discovery made in paper (8) and confirmed in (12) is that most substorms have more than one expansion onset. Arguments concerning substorm phenomena appear to be a consequence of different choices of onset time under the assumption that only one onset was possible. Problems of this nature were reviewed critically in papers (5), (24), (31), (32), and (37).

Recently we have applied the technique of linear prediction filters to the problem of magnetospheric substorms. In paper (44) we showed that the AL index which measures the strength of the westward electrojet is closely related to the solar wind electric field. However, sudden changes in the index are not predictable and appear to be related to changes in the geomagnetic tail. In papers submitted recently, (48) and (50), we conclude that the westward electrojet is connected by currents to both the solar wind and the tail.

TABLE 4

ONR Publications Relating to Magnetospheric Substorms

2. Caan, M.N., R.L. McPherron, and C.T. Russell, Solar wind and substorm related changes in the lobes of the geomagnetic tail, J. Geophys. Res., 78(34), 8087-8096, 1973.

3. McPherron, R.L., C.T. Russell, M.G. Kivelson, and P.J. Coleman, Jr., Substorms in space: The correlation between ground and satellite observations of the magnetic field, Radio Sci., 8(11), 1059-1076, 1973.

5. McPherron, R.L., Critical problems in establishing the morphology of substorms in space, in Magnetospheric Physics, edited by B.M. McCormac, D. Reidel Publ. Co., Dordrecht, 335-347, 1974.

6. Caan, M.N., R.L. McPherron, and C.T. Russell, Substorm and interplanetary magnetic field effects on the geomagnetic tail lobes, J. Geophys. Res., 80(1), 191-194, 1975.

7. Clauer, C.T. and R.L. McPherron, Mapping the local time-universal time development of magnetospheric substorms at midlatitudes, J. Geophys. Res., 79(19), 2811-2820, 1974.

8. Clauer, C.R. and R.L. McPherron, Variability of midlatitude magnetic parameters used to characterize magnetospheric substorms, J. Geophys. Res., 79(19), 2898-2900, 1974.

9. Horning, B.L., R.L. McPherron, and D.D. Jackson, Application of linear inverse theory to a simple current model of the magnetospheric substorm expansion, J. Geophys. Res., 79(34), 5202-5210, 1974.

11. Caan, M.N., R.L. McPherron, and C.T. Russell, Magnetospheric substorms: A computerized determination and analysis, UCLA, IGPP Publication No. 1380-58, 1974.

12. Pytte, T., R.L. McPherron, and S. Kokubun, The ground signature of the expansion phase during multiple onset substorms, Planet. Space Sci., 24, 1115-1134, 1976.

13. Pytte, T., R.L. McPherron, M.G. Kivelson, H.I. West, Jr., E.W. Hones, Jr., Multiple satellite studies of magnetospheric substorms: I. Radial dynamics of the plasma sheet, J. Geophys. Res., 81(34), 5921, 1976.

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Appendix A

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