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## BACKGROUND INFORMATION

NASA research grant NGL 05-007-004 was awarded to the Institute of Geophysics and Planetary Physics of the University of California, Los Angeles, on March 1, 1962, in support of a space instrument development program. The participation of graduate students at the University is a basic part of the research effort.

The grant was renewed on July 1, 1963, with provision for a three-year step funding arrangement. Additional supplements were provided in July 1964, July 1965, October 1966, October 1967, October 1968, October 1969, October 1970, and October 1971.

The investigators whose work is supported under this grant, in the course of this work, have participated or are participating in the following spaceflight missions: Mariners 2, 4, and 5 planetary flybys; OVI-2 and OVI-12 earth satellites, both USAF; the ATS 1, OGO 5, and OGO 6 earth satellites; the Apollo 15 and 16 lunar satellites; and the Pioneer 10 Jupiter flyby. They are participating in preparations for flight experiments for the ATS F and G earth satellites, and Pioneer G Jupiter flyby. Fabrication of the flight hardware for these experiments is funded under separate contracts.

During the reporting period four new proposals were prepared by the investigators. The major portion of the proposal work was supported under this grant.

## I. Charged Particle Research

### A. Theoretical Studies

#### 1. Numerical Models of Convection

A Fortran program has been developed to calculate particle trajectories in a given magnetic field and electric field configuration. This program can be used to calculate pitch angle distributions of particles at a fixed point in the magnetotail for various models of the initial particle distribution at the time an electric field is established across the tail. Further implementation of this program requires an accurate model of the tail magnetic field. To date no suitable model has been found. Several recently published magnetic field models (Mead and Fairfield 1972, Willis and Pratt 1972, W.P. Olson private communication) have been investigated and were found to give either unphysical tail magnetic field configurations or field magnitudes in poor agreement with measured fields.

#### 2. Interpolation by Cubic Splines

Magnetospheric particle fluxes are typically measured in a limited number of energy channels and frequently at only a limited number of pitch angles. For the purpose of comparing theory with experiment, it is useful to obtain the particle flux at constant energy and pitch angle. To this end interpolation by the method of cubic splines has been studied. The problem of interpolation of particle fluxes is complicated

by statistical scatter in the data. To study this problem a weighted cubic spline interpolation routine developed by Powell [1970] was obtained. Tests of this routine weighting the data as the inverse of the standard deviation indicate that this technique is satisfactory for interpolation between energy levels and pitch angles. A modified version of this routine is currently being incorporated into the analysis library of the OGO-5 electron spectrometers.

### 3. Particle Diffusion in the Magnetosphere

The transport of energetic charged particles in the magnetosphere is analyzed theoretically on the basis of a diffusion equation. The assumptions required to justify this description of the transport problem are being reexamined. The purpose of this study is to determine whether the validity of the diffusion equation in magnetospheric problems is justified in all cases.

#### B. Experimental Work

##### 1. Detached Plasma

In the last reporting period we have commenced a study of the phenomena observed in regions of enhanced plasma density beyond the plasmopause. These regions provide, in many cases, the conditions necessary for the development of instabilities, and we encounter a variety of coupled wave-particle phenomena whose properties we are investigating.

## 2. Betatron Acceleration

Following the onset of substorms, a rapid increase in magnetic field strength is often observed near the magnetic equator in the near tail. Simultaneous increases in the flux of energetic electrons occur frequently. We have initiated an investigation of the conditions required for this type of event to be correlated with the presence of ELF hiss.

## 3. Program Development for OGO-5 Electron Spectrometer Measurements

We have been developing a program which will process the particle flux measurements of the OGO-5 electron spectrometer in conjunction with the pitch angles measured by the OGO-5 fluxgate magnetometer to provide data in a form immediately useful for analysis. This program uses the spline fitting method discussed above to obtain from the measurements a function  $j(\alpha, E)$ , the differential directional flux at given pitch angle and energy. This function is parametrized by a limited number of variables which can readily be examined to study evolution of pitch angle distribution and of spectral form.

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- Willis, D.M. and R.J. Pratt, A quantitative model of the geomagnetic tail, J. Atm. Terr. Phys., 34, 1955-1976, 1972.

## II. Magnetic Fields Research

### A. Instrument Development

Instrumentation development is continuing with extensive work on the development of inexpensive ring core magnetometer sensors using commercially available components. In the near future temperature stability, sensitivity and noise tests will be performed on a group of new sensors.

New electronic components present ever changing and rewarding opportunities for advancing state of the art of circuits. Emphasis in circuitry is on simplification of circuits with improved performance. We will continue to develop improved magnetometer circuits to complement the new sensors.

Investigation into low noise preamplifiers for induction coil magnetometers for use in micropulsation detectors is in progress and will continue.

Noise measurements in the magnetometers operating range (infrasonic frequency) have long been a problem. Techniques have been developed at UCLA using digital data logging, followed by computer analysis, which precisely measure and plot noise spectra. These techniques will be improved to facilitate more rapid processing of noise measurements.

### B. Experimental Work

#### 1. ATS-1 Project

##### a. Introduction

In this section we summarize our progress in the area of magnetic fields research, experimental work, ATS-1 project. In



our proposal of September 11, 1972, we outlined four major areas of work we planned to continue. These areas included data processing, data analysis, scientific studies, and support of other projects. In keeping with the guidelines for preparation of this progress report, i.e., brief and informal, we have asked each staff member who has received some support from the grant to prepare a progress report. These reports are collected below under the four major headings listed above and in the same order as our original proposal. In several cases we have initiated new work not discussed specifically in the proposal and identify this work as "new projects."

i. Data Processing

1) Data Submission to NSSDC  
(Lew Randerson, programmer)

Data submission to NSSDC is close to completion. A final report on the ATS-1 correction procedure has been sent in. Data files, except for ephemeris tapes, have been sent in. Tape printouts, except for ephemeris, have been also sent in. Cal Comp plots for 2.5 minute averages have been sent in.

The 15 second averages are three-fourths completed. The fluctuation data and ephemeris data have not been started.

2) Non-Inertial Spin Demodulation  
(Lew Randerson and Neal Cline, programmers)

The work in this area has been directed toward construction of efficient programs for determination of the spin period continuously and accurately from the data itself. Because of its potential speed we chose as our method a phase-lock, tracking technique

which has thus far given very poor accuracy. Consequently we are now setting up a direct Fourier transform peak-detection method which will be less efficient but will guarantee the accuracy we need.

ii. Data Analysis

1) Development of Block Data Sets for General Data Processing (Neal Cline, Programmer)

The block data set designed by us for storage and manipulation of multi-component, multi-segment time series has proven successful even though not all the necessary manipulation programs have been completed. All of the corrected ATS-1 data has been stored in this form, and programs are now available to generate block data sets from most other data sources, in particular the Tungsten magnetometers, the OGO-5 magnetometer, the ground observatories and their associated geomagnetic indices, and Explorer 33 and 35 data. Programs to select segments (with only start and stop times as input parameters) are now working, as well as programs providing listings and Cal Comp plots of the contents of any block data set. The plotting programs have proved particularly useful in a variety of investigations because they have eliminated the tedious task of new programming for every new type of data display. The major manipulative stumbling block at the present time is the process of merging block data sets from disparate sources while insuring time synchronization. This difficulty should be removed shortly.

The remaining work consists of the incorporation of filtering and Fourier transform programs into the block data set system

together with plotting programs for the display of spectra stored in block data set form. Also it has become clear that editing programs will be very useful, enabling us to add and delete components and create new derived quantities.

2) Development of New Spectral Analysis Programs (Marlies Emig, Programmer)

Our spectral analysis of ATS-1 uses two major techniques. First we perform eigen and coherency analysis of the 3x3 cross spectral matrix of any vector time series. The results of this analysis are displayed with standard Cal Comp plot programs. Second, we do dynamic coherency analysis of the 2x2 cross spectral matrix for any selected pair of field components. Results of this analysis are displayed in several ways, including printer maps (line contour, shaded) and Cal Comp plots. As part of these maps we plot to the same time scale the original wave forms of the components analyzed.

We have improved on all of the above programs for spectral analysis in order to cut down on running time and cost. We have broken the analysis into multiple step jobs according to the different phenomena being studied, i.e., Pc 1, Pc 4, and Pi 1 events.

The first step in each program handles collecting the data and creating an old BDS. To do this we have developed interface programs which allow us to use new BDS as input. On both kinds of data sets we perform the different techniques of analysis, as the last step follows the various kinds of plot programs.

3) Development of New Survey Programs Using Complex Demodulation, (Michael Bossen, Student)

In our proposal we described a procedure for dynamic spectral analysis using complex demodulation. This procedure reduces the number of calculations required over our present methods by carrying out the spectral analysis in equally spaced logarithmic frequency intervals rather than linearly spaced. Also, by using a procedure of low pass filtering and decimation, progressively lower frequency spectral estimates are calculated using fewer and fewer data points. The analysis program is broken into a number of models of decreasing complexity. At the higher level is a control program that introduces required parameters conveniently and breaks the input vector time series into overlapping segments. Next is a module that calculates the complete spectral matrix for three third octave frequency intervals then low pass filters the input time series, eliminates every other point and passes this new series back to the input of this module for analysis in the next lower octave.

Within the octave module are a number of smaller modules for calculating the complete spectral matrix. Each spectral estimate is calculated by band pass filtering the input time series, then finding the variance of the filter output. The band pass filtering is accomplished by complex demodulation, i.e., the input waveform is multiplied by a sine and cosine series to shift a portion of its spectrum to zero frequency. The frequency of the sine and cosine are chosen such that the corresponding frequency desired is the lower edge of the band pass filter and translated to zero. The signal waveform which results from this process is then low

pass filtered with a filter cutoff corresponding to the translated upper edge of the desired band pass filter. The advantages of this procedure are that all filters can be realized by simple cascaded running means in which one can easily handle running data points.

At the present time we have developed the overall program as outlined above, coded and debugged most of the lower level modules. The next step in this work will be the coding of the central program and the integration of all modules.

### iii. Scientific Studies

#### 1) ULF Wave Activity during Substorms (Robert McPherron, Professor)

In several separate projects we are studying the properties of ULF waves in space (e.g., see the following report). These studies are initially emphasizing the microscopic properties of these waves and only incidentally examining correlations. Similarly in other projects we have been studying the macroscopic properties of the earth's field as it changes configuration during substorms and storms. To bring together these separate projects we have initiated a new project to study the relation of ULF waves to substorms at synchronous orbit.

Substorm associated phenomena at synchronous orbit include a number of distinct phenomena such as transverse Pc 1 waves, mixed mode, meridional Pc 5, expansion phase irregular pulsations, and transverse Pi 1 (or Pc 3?) waves. To study the role of these waves in substorms we have examined a number of substorm sequences

in which we have detailed information on the solar wind, geomagnetic tail, and ground magnetic disturbances. During these events ATS 1 passes through the midnight sector progressively observing the various wave phenomena in different phases of the substorm. We have carried out eigen and coherency analysis on the spectral matrix for each event and dynamic coherency analysis. We are attempting to describe the conditions required to produce the various types of wave modes characterized by these analysis techniques.

2) Study of Band Limited Pi 1 Micropulsations (Carlene, Arthur, Student)

Pi 1-Pc 3 micropulsations on the ground and in space are being studied using dynamic and cross spectral analysis. Ground events, from the search coil magnetometer at the ATS-1 conjugate point at Tungsten, N.W.T., are quite variable in their nature. Of 11 events which have been analyzed in detail, one appears to be purely Pi 1; another appears to start with Pi 2 bursts, then have a long interval of Pi 1 activity which slowly changes into Pc 3 activity as the station passes the dawn meridian. Several other events seem to have similar character, but have not been completely analyzed yet. Other events are even more complex, and require further detailed study. At this time, it appears possible that some effect, perhaps of the ionosphere, which changes as the ground station passes into sunlight, might explain the apparent evolution of Pi 1 activity into Pc 3 activity. Additional events are being examined to determine whether this is true.

Eleven Pi 1-like events have also been studied in the ATS-1 data. These events are slightly less variable in character,

but are not as strong or as frequent as on the ground. Their characteristics seem more like those of Pc 3 as seen at the ground station. However, at this time, not enough simultaneous ground-satellite events have been studied to make a certain distinction.

In addition to the detailed analysis, a routine survey of the two data files has been made to determine the approximate local time distribution of the events. In space, the waves are seen most often in the hours slightly after dawn. On the ground, if Pi 1 and Pc 3 events are included together, they are seen most often just before dawn.

3) Substorm Signature at ATS-1  
(Savithri Subbarao, student)\*

It has been reported in the literature [Coleman and McPherron, 1970] that the occurrence of a substorm is accompanied by a recovery of the depression in the H component of the magnetic field at ATS 1; the delay of this recovery relative to the occurrence of the corresponding substorm expansion (indicated by the time of the negative bay at local midnight) was studied. It was tentatively concluded, on the basis of the analysis of data from March 1967 that the delay between the recovery in H and the midnight expansion was little, or zero, when ATS 1 was in the midnight to early morning local time sector. This was then taken to be the substorm signature at synchronous orbit. To test the validity of this conclusion, the data sample was expanded to include all data from 1967 and 1968. All occurrences of depressed H

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\*New Project

field at ATS 1 substorm expansion determined from ground records (auroral zone and midlatitude), and the delay of the recovery with respect to the expansion time was calculated. These delays showed no systematic decrease as ATS 1 progressed toward local midnight, as expected. Neither was there any systematic behavior when the delay was taken with respect to the central meridian of the substorm, which does not necessarily coincide with local midnight [Clauer et al., 1972]. However, it appears that the satellite must be located at least two hours west of the central meridian of the substorm to experience any effects of the substorm. If true, this result can significantly alter theories of particle injection into the near magnetosphere during times of substorm activity.

Before this conclusion can become well established, the ambiguity in the identification of substorm onsets on the ground, as well as of the onset of depressed H field at ATS 1, needs to be removed. Towards this end, a set of quiet day curves for ATS 1 are being computed at present. It is hoped to produce different sets of curves to properly take into account the varying conditions of the solar wind, and seasonal variations. Once these curves are available, departures from quiet time behavior in all components of the magnetic field at ATS 1 will become easily identifiable, and it is hoped that an unambiguous substorm signature for H, D, and V at synchronous orbit can be established.

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Clauer, C.R., R.L. McPherron, B.L. Horning, and N.E. Cline, Midlatitude magnetic maps of disturbances due to magnetospheric substorms, paper presented at 1972 Fall Annual Meeting of the American Geophysical Union, San Francisco, Calif., December, 1972.

iv. Support of Other Projects

1) Substorm Signature in the Lobe of the Tail (Michael Caan, Student)\*

Variations in the magnetic energy density in the lobes of the geomagnetic tail appear to play a fundamental role in magnetospheric substorms. The UCLA fluxgate magnetometer on OGO 5 has been used to study the correlation of this energy density with both the solar wind dynamic pressure and the southward component of the interplanetary magnetic field. Positive correlations were found in both instances. The application of good-fitting, least-squares fit reduction, and confidence surfaces to the OGO-5 data has yielded an empirical relationship between the solar wind dynamic pressure; the tail lobe magnetic energy density, and the spacecraft distance down the tail. When the tail lobe field as measured by OGO-5 began to return to its quiet time values, substorm expansion phase onsets were observed both at synchronous orbit, using the UCLA fluxgate magnetometer on ATS-1, and on the ground, using both auroral zone and mid-latitude magnetograms.

A report of this work has been given at the Fall 1972 meeting of the AGU [Caan et al., 1972]. At this time further work

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\*Most of this work is being carried out under our NASA grant to study OGO 5 magnetic field observations. Recently this work was placed under our general support grant and will appear in this report at future times.

is being done on the solar wind dynamic pressure/lobe energy density empirical relationship, and a paper is in preparation to be submitted to the Journal of Geophysical Research.

2) Pc 1 Micropulsations at Synchronous Orbit and Their Role in Magnetic Storms\* (Michael Bossen, Student)

ATS-1 satellite observations of Pc 1 micropulsation activity have provided an important picture of the magnetospheric characteristics of Pc 1 waves. Pc 1 micropulsations are thought to play an essential role in the dynamics of substorms and magnetic storms. Correlation of Pc 1 activity with established storm and substorm phenomena indicate that Pc 1 micropulsations are primarily associated with substorms rather than magnetic storms.

A report of this work was given at the Fall 1972 meeting of the AGU (1). Further work includes power spectral analysis and dynamic spectra of Pc 1 events with determination of wave polarization and ellipticity. A paper is in preparation to be submitted to the Journal of Geophysical Research.

3) Intercomparison of Several Magnetometers at a Standard Magnetic Observatory\*\*  
(Robert Snare, Engineer and Marlies Emig, Programmer)\*\*\*

One of the spare OGO-5 magnetometers and the digital data logger was installed in November 1972 at the NOAA, Castle Rock

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\*This work is primarily supported by an NSF grant to study magnetic storms.

\*\*This work is being supported by the NASA general grant under the section on instrument development.

\*\*\*New project.

Magnetic Observatory at Saratoga, California. The data logger records data from the observatory ASMOR system, a Geometrics proton procession magnetometer and two rubidium vapor magnetometers owned by the USGS Earthquake Research Center at Menlo Park. The purpose of the experiment was to gather total field data from each instrument and to determine how closely the various magnetometers would track one another.

Blocked data sets have been created from the incoming data. This data will then be reformatted, the measurements converted to appropriate units and plotted to a common scale. These plots will be compared to determine how closely the various instruments track one another. The programs have been written and are in their final state to create new BDS for plotting.

## 2. Mariner Project

Radial fits of the power spectra of the interplanetary magnetic field have been made from Mariner 4 measurements over the range 1.0 to 1.5 AU and from Mariner 5 measurements over the range 0.7 to 1.0 AU. We have determined how the power density in each frequency band varies with radial distance from the sun. The data were divided into active and quiet times as well as time intervals with a high probability of Alfvén waves. We have determined also the way in which the slopes of the various power spectra change with radial distance. The slopes were found to be close to the value of -1.5. The power spectra fits for the frequency bands will be useful to cosmic ray investigators.

The work on the extended study of the  $B_{\theta}$  effect has just been published (Rosenberg et al., 1973). This effect involving the "north-south" component relates to our discovery that the interplanetary magnetic field lines skew from the radial in the  $r\theta$  plane in the direction away from the equatorial plane (Coleman and Rosenberg, 1971; Rosenberg et al., 1971). The recent extended study of the  $B_{\theta}$  effect compare the Mariner 4 and 5 results with data obtained by the Goddard Space Flight Center experimenters with spacecraft during the low activity years of the solar cycle (Imp 3, Pioneer 6) and with Explorer 34.

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## C. Theoretical Studies

### 1. Solar Wind Model Studies

With an extended steady state model of the solar wind, the effect of latitude dependences in the coronal boundary conditions upon solar wind flow has been examined. Latitudinal variations in the coronal values of temperature, density, and magnetic field magnitude result in a similar latitudinal dependence of these quantities at 1 AU. However, the effect of these boundary variations upon the north-south component of the flow velocity diminishes rapidly with increasing distance from the coronal boundary, and the model continues to predict latitudinal flow away from the equator. The associated magnetic field lines are also then slightly bent from radial away from the equator. Hence, the results obtained by assuming constant coronal boundary conditions are not significantly altered by the introduction of latitudinal variations in the coronal boundary conditions, and the predicted latitudinal flow and magnetic field component at 1 AU result mainly from local magnetic and rotational stresses. The results of this study are presently being prepared for publication.

#### D. STUDENT PARTICIPATION

A basic purpose of our research is to make it possible for students to participate in scientific experiments within the rapidly developing field of space science. The following graduate students have participated in our programs during the period covered by this report.

1. Carlene Arthur, Department of Planetary and Space Science (PSS), is studying the role of Pc 1 and Pc 3 micropulsations in magnetospheric substorms.

2. Joseph Barfield, PSS, completed his Ph.D. and began work with the Environmental Data Laboratory of NOAA at Boulder, Colo. He is continuing his work on magnetic storms and acts as liaison between the scientific community and E.D.L.

3. Michael Bossen, PSS, has recently joined our group and has been studying the occurrence of Pc 1 micropulsations at synchronous orbit using the ATS-1 magnetometer data.

4. Michael Caan, PSS, has recently joined our group and is using OGO-5 magnetometer data as well as a wide variety of correlative data to study solar wind and substorm effects in the lobe of the tail.

5. Mac C. Chapman, PSS, is working on the strong precipitation data obtained from the electron spectrometer on OGO 6.

6. Donald Childers, PSS, is studying the physics of the magnetosphere. He is working with data from OGO 5 and ATS 1.

7. C. Robert Clauer, PSS, has been working for some time with our group as an engineering aid responsible for archiving of

satellite data. He recently enrolled as a student and is presently studying ground magnetic effects of substorms.

8. Bryan Horning, PSS, has transferred to another project and is presently working on the solar wind interaction with the moon.

9. Bernard R. Lichtenstein, PSS, is concentrating his efforts in the area of lunar magnetism and the interaction of the solar wind with the moon.

10. Lawrence Sharp, PSS, is studying lunar magnetism and the interaction of the solar wind with the moon.

11. Savithri Subbarao, PSS, just joined our group. Her current assignment is to study the signature of substorms at synchronous orbit using ATS 1 magnetometer data.

12. Raymond Walker, PSS, is working on a study of electrons in the magnetotail, using data from the electron spectrometer on OGO 5.

13. Edwin Winter, PSS, completed his Ph.D. and is working for IBM producing mathematical models of space environments to check feasibility of various proposed satellite systems.

All of the registered graduate students whose support is provided by these programs are employed as research assistants in classifications normally open to graduate students under long-established UCLA regulations. Their rates of pay are established by the Regents of the University. A considerable effort is made to assign research tasks which are of special interest to the student, but the tasks themselves are not necessarily related



directly or indirectly to any dissertation research that the student may eventually perform.

## E. PUBLICATIONS AND REPORTS

Papers resulting, wholly or in part, from the research supported under this grant are listed chronologically below.

An asterisk denotes a paper completed since the last report.

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## F. ABSTRACTS

Abstracts of papers and talks concerning results of the research performed, wholly or in part, under this grant are included in this section. These abstracts pertain to papers completed during the reporting period and to talks prepared during this period.



Substorm Associated Betatron Acceleration  
in the Near Geomagnetic Tail

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Rapid increases in the flux of energetic ( $E > 50$  keV) electrons occurring primarily at large pitch angles and simultaneous increases in the magnetic field magnitude are observed by the UCLA electron spectrometer and fluxgate magnetometer experiments on board OGO-5. These flux increases are interpreted as resulting from betatron acceleration. A study of the spatial distribution of all such events seen during OGO-5's 1968 and 1969 orbits in the magnetotail indicates that betatron acceleration occurs primarily between  $8 R_E$  and  $12 R_E$  in  $X_{GSM}$ , near the magnetic equator and within  $\pm 3 R_E$  of the midnight meridian. Detailed studies of several events indicates that betatron acceleration occurred during the expansion phase of a substorm and that the corresponding magnetic field increase occurred without rotation after the field had rotated from a tail-like configuration to a more dipole-like configuration.

Observations of the Magnetic and Plasma  
Structure of the Magnetopause

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High-time resolution observations of the internal structure of the magnetopause have been obtained by the flux-gate magnetometer, the search-coil magnetometer, and the Faraday-cup plasma detector on OGO 5. In the simplest cases, the fields in the magnetosphere and magnetosheath are nearly parallel to each other, there is little change of direction of the incident plasma flow, and the ion flux and field magnitude change simultaneously, with the flux inversely proportional to the magnetic pressure. However, the structure of the magnetopause is often complicated by (1) a region of increased field strength inside the flux gradient, (2) an appreciable field component perpendicular to or crossing the magnetopause, and (3) waves with frequency near .5 Hz. Although turbulence is often observed at the field gradients by the search-coil magnetometer, the magnetopause itself is sometimes quieter than either the adjacent magnetosphere or magnetosheath.

An Investigation of Regions of High Density  
Cold Plasma in the Outer Magnetosphere

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Using complementary experiments on board OGO-5, we have studied regions of high density cold plasma which are frequently found beyond the plasmopause near dusk some hours after substorms. ULF waves of 5 $\gamma$  peak to peak amplitude and 20 second period, as well as less intense waves with periods of a few seconds, have been observed in and near the plasma enhancements. There is some evidence of occasional weak currents on the boundaries of these regions. Neither the spectrum nor the pitch angle distribution of energetic (>50 keV) electrons is noticeably affected by the plasma but, when the energetic electron flux exceeds the stable trapping limit and satisfies the conditions for the generation of cyclotron noise, ELF emissions in the resonant 100-200 Hz range are observed. The same phenomena should be observed in experiments in which cold plasma is artificially injected into the radiation belts.

## The Magnetotail and Substorms

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The tail plays a very active and important role in substorms. Magnetic flux eroded from the dayside magnetosphere is stored here. As more and more flux is transported to the magnetotail and stored, the boundary of the tail flares more, the field strength in the tail increases, and the currents strengthen and move closer to the earth. Further, the plasma sheet thins and the magnetic flux crossing the neutral sheet lessens. At the onset of the expansion phase, the stored magnetic flux is returned from the tail and energy is deposited in the magnetosphere and ionosphere. During isolated substorms, the phenomena which occurred during the initial or growth phase of the substorm are reversed.

In this review, we discuss the experimental evidence for these processes and present a phenomenological or qualitative model of the substorm sequence. In this model, the flux transport is driven by the merging of the magnetospheric and interplanetary magnetic fields. During the growth phase of substorms the merging rate on the dayside magnetosphere exceeds the reconnection rate in the neutral sheet. In order to remove the oversupply of magnetic flux in the tail, a neutral point forms in the near earth portion of the tail. If the new reconnection rate exceeds the dayside merging rate, then an isolated substorm results. However, a situation can occur in which dayside merging and tail reconnection are in equilibrium. The observed polar cap electric field and its correlation with the interplanetary magnetic field is found to be

in accord with open magnetospheric models.

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Submitted to Space Science Reviews.

Satellite Studies of Magnetospheric  
Substorms on August 15, 1968  
Note 1. State of the Magnetosphere

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The sequence of events occurring throughout the magnetosphere during a substorm has not been precisely determined. This note introduces a collection of papers which attempts to establish this sequence for two substorms on August 15, 1968. Data from a wide variety of sources are used with the major emphasis being changes in the magnetic field. In this note, we use ground magnetograms to determine the onset times of two substorms which occurred while the OGO-5 satellite was inbound on the midnight meridian through the cusp region of the geomagnetic tail (the region of rapid change from tail-like to dipolar field). We conclude that at least two worldwide substorm expansions were preceded by growth phases. Probable beginnings of these were at 0330 and 0640 UT. However, the onset of the former growth phase was partially obscured by the effects of a preceding expansion phase around 0220 and a possible localized event in the auroral zone near 0320 UT. The onsets of the corresponding expansion phases were 0430 and 0714 UT. Further support for these determinations is provided by data discussed in subsequent notes.

Satellite Studies of Magnetospheric  
Substorms on August 15, 1968  
Note 2. Solar Wind and Outer Magnetosphere

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M.D. Montgomery, Los Alamos Scientific Laboratory

We continue the study of the sequence of events occurring in the magnetosphere during several substorms on August 15, 1968. We show that the onsets of expansion phases identified in the preceding paper at 0220, 0430, and 0714 UT were each preceded by almost an hour of southward solar wind magnetic field. During the entire interval containing these substorms there was no significant change in the solar wind velocity. Intermittent observations of the solar wind particle density and temperature suggest there were no large changes in the dynamic and static pressure. The fact that the solar wind field remained southward after the onsets of two substorm expansions is interpreted as evidence that the expansion is a process internal to the magnetosphere. However, coincidence of an expansion onset with a large fluctuation of the solar wind field makes it impossible to rule out the possibility that the expansion can be triggered externally. Magnetic field observations in the premidnight sector of the synchronous equatorial orbit show that the earth's field here begins to decrease in response to the beginning of the southward solar wind field. Throughout the interval prior to the onset of the expansion (growth phase) the field continues to decrease. During one of the substorms energetic electron precipitation was observed during this growth phase. In

the expansion phase the field at synchronous orbit recovers.



Satellite Studies of Magnetospheric  
Substorms on August 15, 1968  
Note 4. OGO-5 Magnetic Field Observations

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C.T. Russell, University of California, Los Angeles  
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In this note we examine the changes in the magnetic field on the midnight meridian 15 to 8 Re behind the earth. These changes are conveniently divided into two main phases: a growth phase and an expansion phase. The beginnings of the growth phase coincide within experimental error to the arrival of a southward solar wind magnetic field at the dayside magnetopause and also to the beginning of the growth phase at synchronous orbit and ground observatories. During the growth phase the magnitude of the field increases in the lobe of the tail. In the cusp, both the magnitude and the inclination of the field increase. Slow changes in the cross-tail field accompany these effects. Nearly coincident with the onset of the polar substorm the lobe field magnitude begins to decrease, the cusp field magnitude and inclination decrease and there are sudden changes in the cross tail field. About this time the plasma sheet begins to expand. Inside the expanding plasma sheet and associated with the field rotation are large fluctuations in the field. The response of the field at 8 Re was simultaneous with the ground onset while further back at 11.3 and 2.4 Re above the expected neutral sheet the largest changes were delayed by 15 minutes.

Satellite Studies of Magnetospheric  
Substorms on August 15, 1968  
Note 9. Phenomenological Model for Substorms

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In eight preceding papers, two magnetospheric substorms on August 15, 1968, were studied with data derived from many sources. In this, the concluding paper, we attempt a synthesis of these observations presenting a phenomenological model of the magnetospheric substorm. On a basis of our results for August 15, together with previous reports, we believe that the substorm sequence may be divided into three main phases: the growth phase, the expansion phase, and the recovery phase.

Observations for each of the first three substorms on this day are organized according to this scheme. ~~We present these~~ observations as three distinct chronologies which we then summarize as a phenomenological model. This model is consistent with most of our observations on August 15, as well as with most previous reports. In our interpretation, we expand our phenomenological model, briefly described in several preceding Notes. This model follows closely the theoretical ideas presented more quantitatively in recent papers by Coroniti and Kennel [1972a,b,c]. A southward turning of the interplanetary magnetic field is accompanied by erosion of the dayside magnetosphere, flux transport to the geomagnetic tail, and thinning and inward motion of the plasma sheet.

Our observations indicate, furthermore, that the expansion phase of substorms can originate near the inner edge of the plasma

sheet as a consequence of rapid plasma sheet thinning.

At this time a portion of the inner edge of the tail current is "short circuited" through the ionosphere. This process is consistent with the formation of a neutral point in the near tail region and its subsequent propagation tailward. However, the onset of the expansion phase of substorms is found to be far from a simple process. Expansion phases can be centered at local times far from midnight, can apparently be localized to one meridian, and can have multiple onsets centered at different local times. Such behavior indicates that in comparing observations occurring in different substorms careful note should be made of the localization and central meridian of each substorm.

## Study of $\theta$ -Component of Interplanetary Magnetic Field

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Measurements of the interplanetary magnetic field taken with Imp 3, Pioneer 6, and Explorer 34 constitute a large portion of the data available at low and moderate solar activity and provide nearly continuous coverage from mid-1965 through 1966 without radial effects. A study using these observations provided further evidence for the following  $B_\theta$  effect initially discovered with Mariners 2, 4, and 5. The study found that at low or moderate solar activity the mean value of  $B_\theta$  is negative (approximately northward in our observations) above the solar equatorial plane and positive below it for an interplanetary field directed outward from the sun, and vice versa for an inward field. Thus, for an outward field, the  $r$ - $\theta$  component of a line of magnetic force above or below the equatorial plane was skewed relative to  $\hat{r}$  in the direction away from the equatorial plane. Comparison between different spacecraft are discussed.

Solar Wind and Substorm Related Changes in the Lobes  
of the Geomagnetic Tail

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Variations in the magnetic energy density in the lobes of the geomagnetic tail appear to play a fundamental role in magnetospheric substorms. Data from the ARC fluxgate magnetometers and the MIT plasma probes have been used in conjunction with data from the UCLA fluxgate magnetometer on OGO-5, to study the correlation of this energy density with both the solar wind dynamic pressure and the southward component of the interplanetary magnetic field. Positive correlations are found in both instances. The lobe energy density was found to increase from  $\sim 25\%$  to as much as double its initial value, following a southward turning of the interplanetary magnetic field. Similarly, increases in the solar wind dynamic pressure alone were subsequently followed by lobe energy density enhancements of  $\sim 15\%$  to  $\sim 85\%$  above the initial values. When the tail field as measured by OGO-5 began to return to its quiet time value, substorm expansion phase onsets were usually observed both at synchronous orbit, using the UCLA fluxgate magnetometer on ATS-1, and on the ground, using both auroral zone and mid-latitude magnetograms.

## An Application of the Linear Inverse Theory to Parameterization of Substorm Field-Aligned Current Models

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The geomagnetic components of the magnetic field from eight low-latitude ground stations are studied for substorms occurring on December 24, and 25, 1966. The changes in the field during the expansion phase are analyzed in terms of simple wire models of field-aligned currents. The basic model has four parameters; the current magnitude, the L-shell on which the current flows, and the local times of the eastern and western portions of the circuit. The linear inverse problem is constructed and the Wiggin's cutoff technique is utilized to find the set of model parameters which best fit the data. The four parameter model, while producing good qualitative fits, is unable to fit the data within two standard deviations of the error in the observations. The best fits to the ground data are shown to be nearly independent of the L-shell parameter. Typical values of the parameters for the substorms studied are one million amps for the current, and 0200 LT and 2100 LT for the eastern and western elements of the circuit.

Pc 1 Micropulsations at Synchronous Orbit  
and Their Associations with Magnetic Storms

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Pc 1 micropulsations are thought to play an essential role in the dynamics of substorms and magnetic storms through the cyclotron instability of ring current protons. Ground observations of Pc 1 are distorted by effects of wave propagation, making it difficult to predict their original properties. Magnetospheric observations of these waves by the UCLA magnetometer on ATS 1 indicate they are fairly common, occurring with amplitude  $\geq 1 \gamma$ , 121 times during 1967. Typical periods are from 2 to 5 seconds with typical peak to peak amplitudes of 1 to 7  $\gamma$ . These waves are most probable at 1600 local time and are characteristically associated with high values of the AE index. Almost every Pc 1 event begins within two hours after the onset of a substorm expansion. A few closely follow storm sudden commencements. Of the events, 48 occurred within a magnetic storm, 20 of these within  $\pm 4$  hours of the main phase minimum. The properties of these storm associated events will be contrasted to the remaining events with particular emphasis on their relation to the ambient field magnitude and Dst.

## On the Cause of Geomagnetic Storms

C.T. Russell and R.L. McPherron  
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Noting that the size of sudden commencements of geomagnetic storms was independent of the magnitude of the associate main phase minimum, Piddington in 1963 concluded that geomagnetic storms all resulted from solar winds of the same average intensity and duration and speculated that the different main phase intensities result from differing degrees of frictional interaction, the difference perhaps depending on the interplanetary magnetic field strength and direction. Studies of the solar wind velocity, and density as measured by the MIT plasma probes, and the interplanetary magnetic field strength and orientation as measured by the Ames fluxgate magnetometers, on Explorers 33 and 35 during geomagnetic storms, confirm this picture. A strong southward component of the interplanetary field is the only necessary element in the growth of the main phase of a geomagnetic storm. The data suggest that there is a threshold field of 5  $\gamma$  southward which when exceeded leads to the development of a storm. If this threshold is not exceeded the ring current does not increase in strength no matter how long the southward field exists.

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