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JUNE 1987 GISMOS EXPERIMENT: PRELIMINARY REPORT ON HIGH TIME RESOLUTION, MULTI-RADAR MEASUREMENTS

C. R. Clauer,* J. D. Kelly,** M. Lockwood,*** R. M. Robinson,† J. M. Ruohoniemi,‡ O. de la Beaujardiere** and L. Hakkinen§

**Space Telecommunications and Radioscience Laboratory, Stanford University, Stanford, CA 94305, U.S.A.; **Geoscience and Engineering Center, SRI International, 333 Ravenswood Ave., Menlo Park, CA 94025, U.S.A.; ***Rutherford Appleton Laboratory, Chilton, Didcot, OX11 0QX, U.K.; †Space Science Laboratory, Lockheed Palo Alto Research Laboratory, Palo Alto, CA 94304, U.S.A.; ‡Applied Physics Laboratory, Johns Hopkins University, Laurel, MD 20707, U.S.A.; §Department of Geophysics, Finnish Meteorological Institute, Box 503, SF–00101 Helsinki, Finland*

ABSTRACT

Data collected by ground magnetometers and high latitude radars during a small isolated substorm are discussed in terms of the global changes in convection during the substorm. This substorm was observed during the international GISMOS (Global Ionospheric Simultaneous Measurements of Substorms) Experiment of 1 - 5 June 1987 and the array of observations discussed here span the night sector from approximately dusk to dawn. The substorm, observed by the Sondrestrom radar and auroral and midlatitude magnetometers is associated with a polar cap contraction observed near dusk by the EISCAT radar.

INTRODUCTION

The goals of the GISMOS (Global Ionospheric Simultaneous Measurements of Substorms) experiments are "to obtain simultaneous, synergistic, and global measurements of the ionosphere and magnetosphere; to analyze individual events in detail to understand the time varying aspects of the coupling between the magnetosphere and the ionosphere; to provide realistic inputs and boundary conditions for modeling magnetospheric processes; to provide observations against which the model predictions can be tested; and to foster comparisons and interconnections among the models" /1/. A particular goal of the coordinated multi-instrument GISMOS data collection and analysis efforts is to delineate the flow of energy from the solar wind through the magnetosphere to its ultimate dissipation in the ionosphere. Since the ionosphere forms one of the electrical boundaries of the solar wind - magnetosphere - ionosphere system, various manifestations of the transmission of the energy through the magnetosphere appear in the ionospheric plasma. Primary among these manifestations is the dynamic behavior of the high latitude ionospheric electric fields, currents and conductivity. The particular organization of the June 1 - 5, 1987 GISMOS radar operations focused upon obtaining high latitude electrodynamic measurements at high time resolution in order to investigate high latitude large scale electrodynamic parameters during time varying conditions and substorm activity.

The processes which influence substorm activity begin on the dayside of the Earth where the solar wind and interplanetary magnetic field first encounter the magnetosphere. A few percent of the kinetic power carried by the solar wind plasma impinging upon the dayside magnetopause (between 10^{11} and 10^{12} Watts) enters the magnetosphere to drive currents, energize plasma, and produce a complex pattern of plasma convection /2,3/. Much of the extracted solar wind energy is thought to be ultimately dissipated as heat in the Earth's upper atmosphere, while another portion of the extracted energy is thought to be returned to the solar wind by plasmoids which are ejected down the magnetotail during intervals of substorm activity.

The coupling processes which occur at the magnetopause can be divided roughly into two categories. The first is electromagnetic coupling which involves interactions between the solar wind magnetic field and the geomagnetic field (eg. reconnection). The second coupling is non-magnetic and is generally referred to as a "viscous interaction" (eg. Kelvin-Helmholtz driven waves, cross field diffusion, impulsive penetration, or gradient-drift entry). It appears, however, that electromagnetic coupling provides the major momentum exchange between the solar wind and the magnetosphere /4,5/, though there remains considerable debate regarding the possibility that the viscous interactions could be an important or dominant coupling mechanism under some conditions /6,7/ and references therein). The rate of energy coupling, and hence the strength and orientation of the associated electrical current systems, vary with the velocity and orientation of the IMF. Geomagnetic activity and particularly substorms appear to result from both increased energy coupling and also from sudden changes in the coupling rate /8,9/.

In this report we provide a preliminary discussion of a set of spatially separated data which describe the global dynamics of the auroral oval and polar cap prior to and during a small isolated substorm.

OBSERVATIONS

The period of particular interest in this analysis is the interval from 01 - 05 UT on 5 June 1987. It is an interval characterized by a weakly southward IMF and a small, isolated magnetospheric substorm onset at about 03:45 UT. Prior to this substorm, another small, isolated substorm occurred at about 00 UT following another interval of southward IMF.

Figure 1 shows magnetograms from two auroral zone stations: Leirvogur, Iceland and Poste de la Baleine, Canada. Leirvogur is near local midnight at the onset of the first substorm prior to the event under consideration and the characteristic negative bay signature of both substorms can be seen in the Leirvogur H component. The onset of the substorm under consideration here is ooserved at Leirvogur (04 MLT) at03:45 UT. Poste de la Baleine, near 23 MLT, observes the onset at 03:55 UT. The maximum perturbation in the H component during the substorm is about 150 nT and occurs at abut 04:30 UT in the Poste de la Baleine magnetogram. Thus, in terms of the strength of the substorm expansion phase westward electrojet observed near magnetic midnight, this is a moderately small substorm. Mid-latitude stations in the midnight sector recorded positive bays in the H component of about 10 nT. The end of the recovery phase of the substorm occurs at about 05:00 UT.

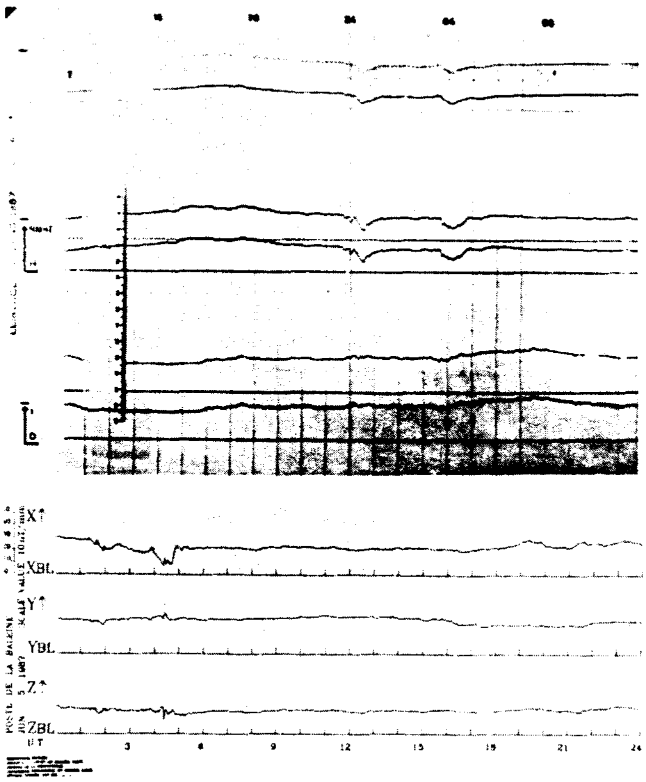

Fig. 1. Magnetograms from Leirvogur, Iceland (top) and Poste de la Baleine, Canada (bottom) for June 5, 1987. A Substorm onset is observed in the H component of Leirvogur at 03:45 UT and in the X component at Poste de la Baleine at 03:55 UT.

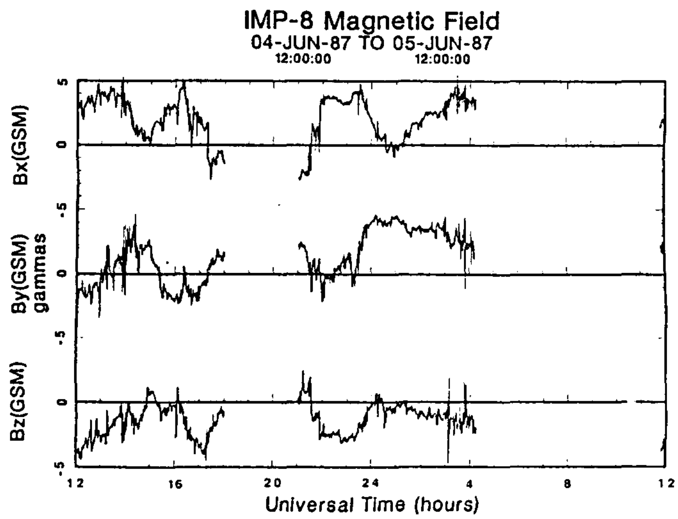

Fig. 2. Interplanetary magnetic field measured by the IMP-8 satellite from June 4, 1987 12 UT to June 5, 1987 12 UT in GSM coordinates.

The interplanetary magnetic field measured by IMP-8 is shown in GSM coordinates in Figure 2. The first substorm expansion at 00 UT followed a roughly 2 hour interval of southward IMF ($B_z \simeq -3.5nT$). The 03:45 UT substorm was preceded by about 2.5 hours of weakly southward IMF ($B_z \simeq -2nT$). The onset of the substorm expansion is proximate to the sudden northward fluctuations in B_z observed at 03:48 UT. The expected propagation delay, assuming the positive fluctuation to lie in a plane aligned along the Parker spiral or othogonal to the Earth-sun line, between IMP-8 and the magnetopause is about 5 - 8 minutes. Therefore, unless the northward fluctuation lies in the plane normal to the Parker spiral, it is an unlikely trigger for the substorm onset. Unfortunately, a data gap in the IMP-8 data follows 04:13 UT.

In Figures 3 and 4 we show the ionospheric plasma convection measured respectively by the Sondre Stromfjord and EISCAT incoherent scatter radars. These are clock dial plots with local time shown around the outside of the plot and universal time shown around the interior of the dial. Invariant latitude forms the radial dimension. A vector in

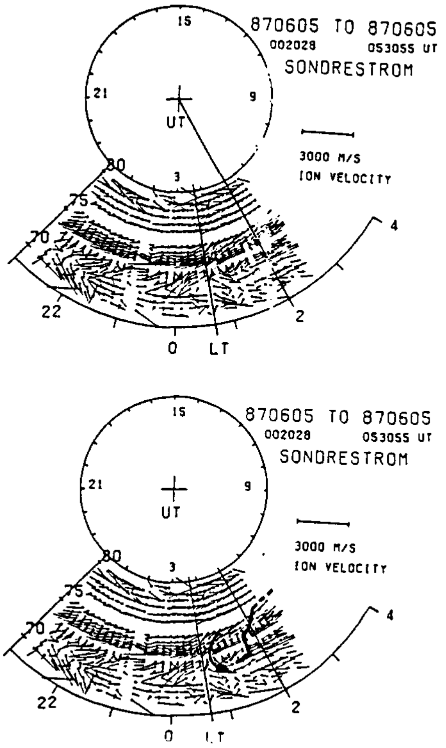

Fig. 3. F-region ion convection measured by the Sondrestrom radar in a clockdial format with UT measured around the inner circle and geographic LT measured around the outer circle. In the bottom panel we add schematic markings on the data to aid the viewer in observing the features described in the text.

the direction of the velocity is shown at each measurement point. We have indicated the 03:45 - 05:00 UT substorm interval on both plots with radial lines. During the substorm, the Sondrestrom radar is located in the post midnight local time sector and EISCAT is located near dawn.

Prior to the substorm expansion onset, Sondrestrom appears to observe a gradual equatorward motion of the convection reversal boundary from 75° invariant to about 73° invariant during the interval 02:30 to 03:45 UT. This equatorward motion of the polar cap boundary is taken to represent the expansion of the polar cap and to be associated with the accumulation of magnetic flux in the tail lobes as a result of dayside reconnection. At EISCAT near dawn, the convection reversal boundary is observed to be located between 72.5° and 72.6° invariant latitude prior to the 03:48 UT and to begin a rapid poleward contration at this time.

Following the expansion phase onset, the Sondrestrom radar measures plasma flow out of the polar cap during the first half of the substorm interval. During the second half of the interval, Sondrestrom observes the convection reversal boundary to be located initially at about 73° invariant and to then suddenly jump to 76° invariant at the end of the substorm. At EISCAT near dawn, the effect of the substorm is a poleward motion of the convection reversal boundary during the entire substorm interval from 72° to 76° invariant. The contraction of the polar cap during the substorm expansion and recovery phases indicates an imbalance between the merging rates on the dayside and nightside with more flux leaving the polar cap on the nightside than entering it on the dayside /10, 11, 12, 13/. Since the polar cap contraction is observed to continue at EISCAT and the magnetic measurements of substorm activity at auroral and midlatitude observatories indicate that the substorm continues, it is possible that the observed halt to outflow from the polar cap observed by Sondrestrom in the middle of the substorm interval is the result of Sondrestrom rotating past the outflow region. This may be equivalent to moving beyond the ionospheric projection of the substorm merging line in the tail. This is very interesting because it appears that the location of the convection reversal boundary at Sondrestrom is still near 73° invariant and this may indicate a stationary (in position down the tail) merging line at least through the expansion phase of the substorm. The sudden poleward motion of the convection reversal boundary at Sondrestrom during the final 10 minutes of the substorm may be related to the tailward retreat of the merging line.

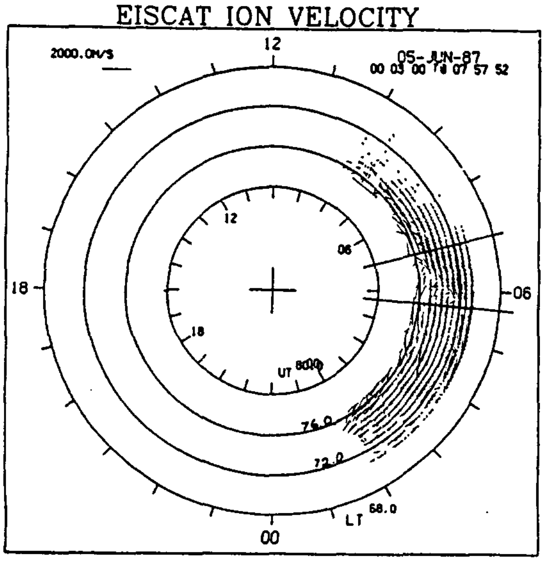

Fig. 4. F-region ion convection measured by the EISCAT radar in a clockdial format similar to the one in Fig. 3. The 03:45 UT substorm interval is marked by radial lines and during this interval the convection reversal is observed to move poleward.

A simple calculation is possible to determine the amount of flux removed from the polar cap during the contraction assuming a circular polar cap centered on the invariant pole and a dipole representation of the geomagnetic field.

$$\Phi = \int B \cdot da \quad (1)$$

The polar cap boundary, initially located at $\Lambda = 72.4°$ moves poleward 4.1° to $\Lambda = 76.5°$ in 75 minutes. This amounts to a change in flux of $2.882 \cdot 10^8$ Webers. The flux rate of change is then given by the outflow across the merging line projection in the ionosphere.

$$\frac{d\Phi}{dt} = V_\perp \cdot B \cdot l \quad (2)$$

where $V_\perp$ is the velocity normal to the boundary (equatorward component of the flow) and l is the length of the merging line projection in the ionosphere. Knowing that the contraction takes 75 minutes, and using the equatorward component of the flow measured at Sondrestrom ($V_\perp \simeq 500$ m/sec.) we can solve for l and find $l = 2.167 \cdot 10^6 m$. This is equivalent to about 5 hours in local time. This gives a potential drop along the neutral line of about 64 kV. A detailed analysis of the EISCAT observations of the convection reversal boundary during this polar cap contraction is presented by Lockwood et al., /13/. They find that during the contraction observed at EISCAT, the poleward component of the plasma velocity exceeds the contraction velocity. That is, there is flow into the polar cap observed at EISCAT. The flow is equivalent to a 7 kV potential drop over about two hours of local time and is attributed to viscous processes at the flanks of the magnetosphere. This observation plus the possibility of additional flow into the polar cap from the dayside merging region indicates that the above estimates of the length of the substorm merging line and potential drop are probably lower limits.

Magnetic records of the substorm are consistent with the large local time extent of the substorm current systems suggested by the above estimates. Following the ideas of Clauer and McPherron, /14,15/ who use midlatitude magnetograms to parameterize the location, extent and magnitude of isolated substorm disturbances we find positive bays in midlatitude magnetograms are observed at Tucson at 21 MLT, Fredericksburg at 23 MLT and San Juan at 23:45 MLT. A positive bay is also observed at the sub auroral station at St. Johns located at 01 MLT. A delayed negative bay is observed at the auroral station Fort Churchill located at 21 MLT and no bay disturbance is observed at Yellow Knife at 19 MLT. Thus the extent of the substorm current wedge is roughly from 21 MLT to 03 MLT.

SUMMARY

A small, isolated substorm observed by the Sondrestrom radar and by ground magnetometers at auroral and midlatitudes is associated with a polar cap contraction observed near dusk observed by the EISCAT radar. The longitudinal extent of the substorm disturbance spans roughly 21 MLT to 03 MLT. Based upon the flow out of the

polar cap observed by the Sondrestrom radar at 02:00 MLT we estimate that the length of the outflow region must be 5 or 6 hours of local time to account for the contraction of an assumed circular polar cap observed by EISCAT. This is consistent with the extent of the disturbance deduced from the magnetic records.
These observations are consistant with a model of magnetospheric substorms in which flux is accumulated in the tail lobes during an interval of enhanced dayside reconnection associated with a southward IMF. This results in an expansion of the polar cap. The contraction of the polar cap and the associated nightside substorm disturbance are the result of an enhanced reconnection rate in the magnetotail, probably at a new near-Earth merging line. The local time extent of the merging line is very broad, and the observation that the night side position of the convection reversal boundary appears to remain constant during the contraction observed at dusk, suggests that the radial position of the merging line also remains fixed until the end of the recovery phase, when we observe a sudden poleward motion of the convection reversal at Sondrestrom. We note that this scenerio is outlined for only simple isolated substorms and may not be the case for more complex periods of continuous activity.

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REFERENCES

1. O. de la Beaujardiere, D. S. Evans, Y. Kamide, and R. P. Lepping, Response of auroral oval precipitation and magnetospheric convection to changes in the interplanetary magnetic field, *Ann. Geophyysicae,5*, 519, (1988).
2. T. W. Hill, Solar-wind magnetosphere coupling, in *Solar-Terrestrial Physics*, edited by R. L. Carovillano and J. L. Forbes, 261 - 302, D. Reidel, Dordrecht, (1983).
3. D. N. Baker, T. A. Fritz, R. L. McPherron, D. H. Fairfield, Y. Kamide, and W. Baumjohann, Magnetotail energy storage and release during the CDAW 6 substorm analysis interval, *J. Geophys. Res., 90*, 1205, (1985).
4. L. C. Lee and J. G. Roederer, Solar wind energy transfer through the magnetopause of an open magnetosphere, *J. Geophys. Res., 87*, 1439, (1982).
5. I. M. Podgorny, E. M. Dubinin, and Y. N. Potanin, The magnetic field on the magnetospheric boundary from laboratory simulation data, *Geophys. Res. Lett., 4*, 207, (1978).
6. P. H. Reiff and J. L. Burch, IMF By-dependent plasma flow and Birkeland currents in the dayside magnetosphere 2. A global model for northward and southward IMF, *J. Geophys. Res.90*, 1595, (1985).
7. W. J. Heikkila, Transport of plasma across the magnetopause, in *Solar Wind - Magnetosphere Coupling*, Y. Kamide and J. A. Slavin (Eds.), 337, Terra Scientific Publishing, Tokyo, (1986).
8. R. L. McPherron, C. T. Russell, and M. P. Aubry, Satellite studies on August 15, 1968, 9: A phenomenological model for substorms, *J. Geophys. Res., 78*, 3131, (1973).
9. M. N. Caan, R. L. McPherron and C. T. Russell, Characteristics of the association between the interplanetary magnetic field and substorms, *J. Geophys. Res., 82*, 4837, (1977).
10. C. T. Russell and R. L. McPherron, The magnetotail and substorms, *Space Sci. Rev., 15*, 205, (1973).
11. R. L. McPherron, Magnetospheric substorms, *Rev. Geophys. Space Phys., 17*, 657, (1979).
12. M. Lockwood and M. P. Freeman, Recent ionospheric observations relating to solar wind - magnetosphere coupling, *Phil. Trans. Roy. Soc., (London), A*, in press, (1988).
13. M. Lockwood, S. W. H. Cowley, H. Todd, D. M. Willis, and C. R. Clauer, Ion flows and heating at a contracting polar cap boundary, *Planet. Space Sci.*, submitted, (1988).
14. C. R. Clauer and R. L. McPherron, Mapping the local time - universal time development of magnetospheric substorms using midlatitude magnetic observations, *J. Geophys. Res., 79*, 2811, (1974).
15. C. R. Clauer and R. L. McPherron, Variability of midlatitude magnetic parameters used to characterize magnetospheric substorms, *J. Geophys. Res., 79*, 2898, (1974).