R. B. Sheldon and H. E. Spence

A New Magnetic Storm Model

Abstract

Recent observations of magnetic storms from the new perspective of the POLAR orbit have elucidated the crucial role that parallel electric fields and the ionosphere play in the development of a magnetic storm. This model has implications for the empirical formulas linking the solar wind with Dst, for composition changes in the ring current, for precipitation and subauroral arcs seen at earth, for ionospheric signatures seen by radar or riometers, and not least of all, energetic neutral atoms. The model predicts that a large polar cap electric field, which persists on the order of an hour or more, exceeds the ability of the tail to shield out the polar cap potential, and produces a strong cross-tail electric field in the plasmasheet. This field convects plasmasheet ions into the inner magnetosphere, where the opposing ∇B and $E \times B$ drifts act as a selective filter permitting a single energy the deepest penetration. This monoenergetic band of ions generates a field-aligned potential drop that attempts to confine the ions to the equator. Thus equatorial electrons are accelerated through the potential and precipitated deep into the ionosphere E-layer where they produce riometer and radar signatures. Simultaneously, ionospheric ions are extracted and energized into the ring current. Ion cyclotron waves, generated by this unstable particle population, then perpendicularly heat these ion beams and scatter them out of the loss cone so that they become a permanent part of the ring current. This entire dynamic structure would rapidly decay if it were not for the continuous power input of the hot magnetospheric ions which in the frame of the ionosphere, convect through the cold plasma population. When the cross-tail field switches off, the convection power source is removed, the parallel electric fields vanish, and the hot ions are trapped in the ring current and subsequently decay through charge exchange.

Introduction

The elements of this new magnetic storm model have all been presented before, but they have lacked a coherent, causal chain, and above all, a quantifiable model that had predictive ability. For example, *Smith and Hoffman* (1974) presented the time-dependent model of ring current injection, but were unable to predict how deep the injection would occur or subsequent Dst development of a storm. Similarly, *Hamilton et al.* (1988) measured the enhanced ionospheric oxygen content of great storms, but were unable to predict which storms or how much oxygen was to be expected. Our model takes as its input the cross-tail potential at the inner edge of the plasmasheet and the plasmasheet density at this location, to predict all of the above quantities. With a suitable inner tail model, we should be able to use only the solar wind density and electric field , $Ey = Bz * Vx$, to make these predictions.

Data Analysis

The POLAR spacecraft is in a polar, 9 x 2 Re orbit that on April 15 was in the noon-midnight meridian with perigee over the south pole. Thus it made two diagonal passes through the midnight and noon radiation belts. A typical pass shows an energetic particle population whose average energy is proportional to the $|B|$. This is the normal distribution for ions diffusing in L-shell from a source region in the plasmasheet (*Sheldon and Hamilton*, 1993). On this day the Comprehensive Energetic Particle and Pitch Angle Distribution (CEPPAD) (*Blake et al.*, 1995) experiment detected two monoenergetic bands superposed on the night side ring current (figure 1): a monoenergetic population of trapped ions at ∼90 keV, and a monoenergetic beam of field-aligned ions at ∼40 keV.

A monoenergetic trapped population is possible when a strong cross-tail electric field drives ions against the ∇B drift deep into the magnetosphere (*Smith and Hoffman*, 1974). Such a "nose" event must be nearly 90° trapped particles because of the large increase in $|B|$ while convecting from the plasmasheet, which is the characteristic of the upper energy band in our data. Support for this hypothesis came from the extensive GGS database.

Examination of WIND data (*Ogilvie et al.*, 1995) for April 14 showed that there were several Bz <0 periods lasting for 1 hour or less. Corresponding AU and AL derived from the CANOPUS array (*Rostoker et al.*, 1995) show that these periods led to substorms with riometer absorption signatures at auroral latitudes. However the storm trigger appears to be the strong southward turning of Bz <-10 occurring at 2000 UT, accompanied by a jump in the solar wind speed from 450 km/s to 600 km/s, which produced an even larger Bz in the compressed magnetic field of the magnetosheath. This period of strong southward Bz lasted more than 3 hours, effectively saturating the ability of the tail to shield out the polar cap potential. The IZMIRAN model (*Papitashvili et al.*, 1994) predicted in excess of 150 kV across the polar cap for these solar wind conditions.

While CANOPUS riometers recorded very little activity at auroral latitudes, the riometer at L=4.4, as well

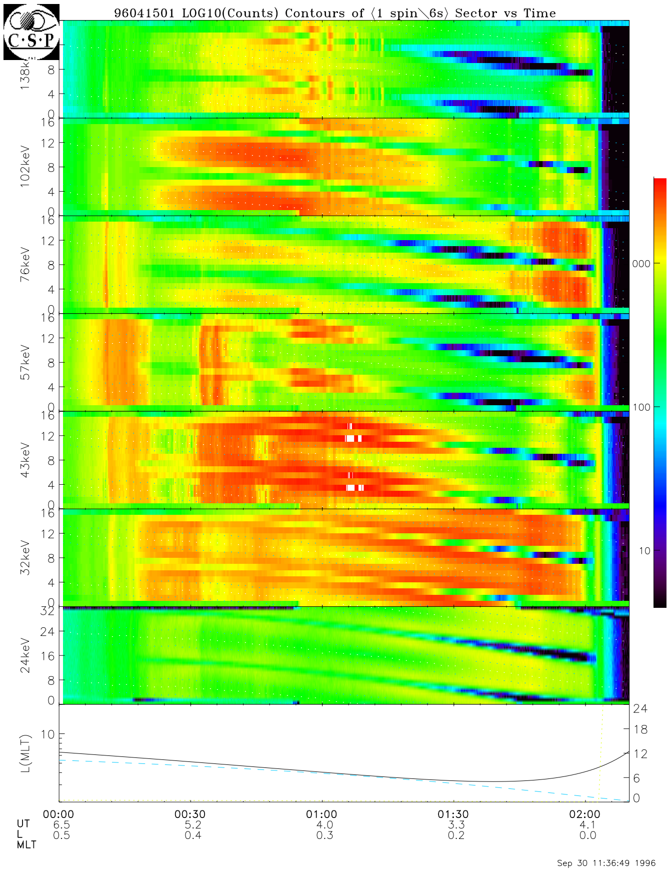

Figure 1. POLAR/CEPPAD/IPS data on April 15, 1996, displaying roll modulation of the counts in the 90° head in the energy bands from 24–138 keV.

as the Halley Bay riometer at L∼4, (private communication A. Rodger, 1996) showed an extremely intense and narrow absorption feature at this time, indicating that precipitation had penetrated to low latitudes, deep in the magnetosphere and down to E-layer ionospheric depths. From these observations, as well as complementary ground observations, we surmise that after several intense substorms had pumped up the plasmasheet, a strong convection field injected the plasma to at least L=4.4, which POLAR/CEPPAD observed as a 90 keV band.

The band of 40 keV field-aligned ions, however, are harder to explain. They have the wrong pitchangles to have convected from the plasmasheet, because the adiabatic decompression involved in backtracing them to their originwould place them in the plasmasheet loss cone. But ions of this energy would not have had access to the plasmasheet simultaneously with higher energy ions, since the magnetosphere is a "notch filter" for only one energy. This implies that these ions are trapped on closed drift orbits. But if they undergo the same processes as the adiabatically energized ring current, which can be seen simultaneously with the banded distribution, they would not be monoenergetic, nor would they track the energy of the nose ions so precisely. That is, if they had resided for any length of time in the magnetosphere, the same convection that brought in the plasmasheet ions would disperse these ions as well. Thus we conclude that these field-aligned ions are *in situ* accelerated during the time of the measurement.

"Zipper" events, (*Fennell et al.*, 1981) (identified first by *Kaye et al.* (1981)), have the same bimodal pitch-angle distributions, though at somewhat lower energy. They found that the "zippers" were rich in O^+, and concluded that they were observing beams coming from the ionosphere. Since beams are seen at auroral latitudes, they concluded that they were on flux tubes connected to auroral arcs. The composition experiment, POLAR/CAMMICE, was turned off during this period, so we cannot determine the $E > 30$keV O^+ content for April 15, however when it was switched back on, around April 20, it found an anomalously large amount of O^+ in the ring current. POLAR/TIMAS *Shelley et al.* (1995) (private communication W.K. Peterson, 1996) did detect $E < 20$keV O^+ beams for this day. So we conclude that on April 15 we are observing O^+ ions accelerated to ∼30–40 keV by strong parallel electric fields in the ionosphere. Since these ions track ∼50 keV below the nose ions, it appears there must be a causal connection.

Whipple (1977) argues that one can produce a field-aligned electric field if the electron and ion pitch angle distributions (PADs) are not identical. In our case, the hot monoenergetic nose ions are superposed on a cold plasmasphere electron population producing a parallel electric field of several kT_e. If the energetic ion density is greater than the plasmaspheric cold electron density, a second ion-dominated solution to the Whipple equations is possible at approximately the ion beam parallel energy.

Figure 2 illustrates how the three populations (ring current, "nose", and beam) evolve during this interval. First, the ring current is adiabatically energized so that as the model equatorial magnetic field increases the energy increases, as noted by the squares and dashed line. This adiabatic energization is not seen by the nose ions because we are not following a single ion trajectory, rather we are seeing the nose ions that have access to this location, so that stronger B-field ions also began with smaller magnetic moment. A more detailed analysis of the pitch angles is needed to clarify the coupled energy-L dependence of these ions. If the first solution to *Whipple* (1977) holds, then both the nose and the beam energies should move in concert as we move along the field line. That is, as we

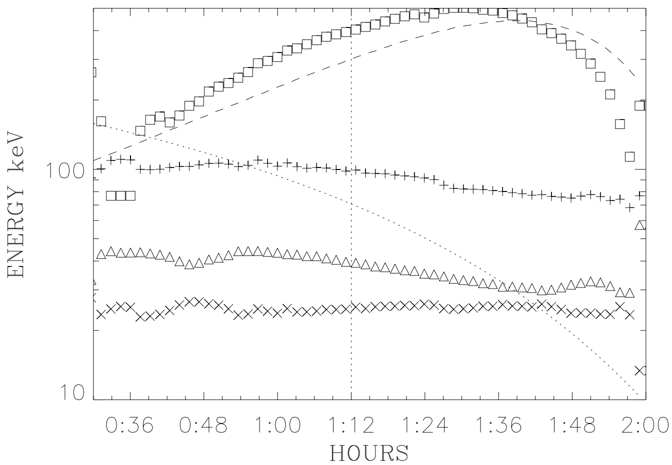

Figure 2. Peak fits to 96s averages of the 90° head. Ring current (square), nose ion (+), and beam ion (triangle) energies plotted versus time. The ratio of nose/beam × 10 is displayed as crosses. Overplotted with different scales are: the model equatorial magnetic field intensity plotted at the same scale from 20–1000 nT; and the model magnetic latitude (dotted line) from -40 to 40 degrees, with the equator marked with a vertical dotted line.

traverse a region of strong potential gradient, we should observe a constant difference between these two energies.

We find instead that the beam ion energy tracks the nose ion energy with a nearly constant ratio of 1/2, and not a constant difference. This suggests that the field-aligned potential gradient is closer to the ionosphere than our orbit, and that the beam energy is not determined by the electron thermal temperatures or anisotropies, but by the energy of the nose ions themselves, consistent with the second, ion-dominated solution to the *Whipple* (1977) equilibrium.

Such a parallel electric field should also accelerate magnetospheric electrons to 30 keV into the ionosphere, producing a riometer absorption event. Since the electric field is colocated with the nose plasma, the absorption must be a narrow strip in latitude but distributed in longitude, as seen in the CANOPUS data. This type of signature is typical of sub-auroral ion drifts (SAID) which have been identified with substorm injections. Our mechanism would identify a SAID with a storm injection, and also accounts for the E-layer keV electron signature seen in subauroral riometer data.

We carefully distinguish between substorm and storm injections because we feel the characteristic signatures of each are completely different. A substorm involves a reconfiguration of the magnetic field which produces a dB/dt electric field in the region between 6-10 Re near midnight. This inductive electric field *in situ* accelerates the entire plasma population to ∼30 keV, which is observed in our instrument as an isotropic, dispersionless <50 keV enhancement over a restricted MLT and L-shell range. A storm injection, on the other hand, is observed as a nose event, a monoenergetic band of ions penetrating to sub-auroral L-shells and existing over a broad range of MLT determined by the duration of the cross-tail field. Energization of low energy plasma is not seen, but adiabatic energization of the nose ions occurs as the ions convect toward stronger B. From an ionospheric viewpoint, substorms are in the auroral zone, whereas storms penetrate down to sub-auroral latitudes albeit in a restricted latitude band.

Discussion

If our mechanism generates field aligned electric fields and oxygen beams for every storm injection, then we have elucidated a new model for magnetic storms. Since it is generally thought that magnetic storms are characterized by intense convection fields that bring plasmasheet plasma deep into the ring current, then all storms should create parallel fields and extract oxygen from the ionosphere as well. Thus large storms should extract more oxygen than small storms, with a larger Dst effect.

Several recent observations lend support for this theory. Analysis of the CRRES data set shows that there is a positive correlation between the magnitude of Dst and the O^+ content of the ring current (*M. Grande*, COSPAR 96 proceedings to be published in *Adv. Sp. Res.*). A Dst prediction filter (*Gleisner et al.*, 1996) found that a neural network with one hidden layer, representing an unknown quadratic dependence on solar wind Vx,Bz, and density, could explain up to 84% of the variance in Dst. If significant O^+ is extracted during the main phase as we predict, one would expect such a non-linear dependence of Dst with Ey.

This extraction of ions and precipitation of electrons near midnight will generate an outward flowing current which then drifts westward with the bulk of the ring current. We expect that the disappearance of the parallel field, occurring near the dusk terminator, will result in a downward current thus completing the loop of the partial ring current as measured by *Suzuki et al.* (1985) using Magsat data. They concluded that 1/3–1/4 of ring current amperage was observed in the partial ring current. If we assume that half of the partial ring current is carried by upward flowing ions, then we estimate that 1/6 - 1/8 of the total ring current is composed of ions of ionospheric origin.

A study of storm-time PC1 pulsations by *Mursula* (COSPAR 96 proceedings to be published in *Adv. Sp. Res*) showed that the PC1 waves associated with ion-cyclotron waves during the most intense part of the main phase of a storm occurred primarily at dusk and the PC1 frequency dropped down to below the oxygen gyrofrequency. These observations are suggestive of an oxygen rich plasma occuring at dusk, the location of the deepest penetration of the nose ions and also in agreement with our theory.

Finally, GEOTAIL/EPIC observed energetic neutral atoms (ENA) during the recovery phase of a magnetic storm (*Lui et al.*, 1996) which showed the same H and O spectra as AMPTE/CCE H^+ and O^+ spectra observed in a 1986 storm (*Hamilton et al.*, 1988). But the time decay of the GEOTAIL species were identical, suggesting that the H^+/O^+ ratio was constant during the recovery phase of a storm. This is not consistent with their different loss cross sections, unless a production mechanism for O^+ is found as we predict above. Recent ENA observations of a storm made with POLAR/CEPPAD show a strong asymmetry consistent with the above picture.

Conclusions

We have attempted to build a new model of magnetic storms that incorporates field-aligned electric fields as an intrinsic part of the storm development. A storm proceeds then with the following steps: 0) It may be necessary to have a critical density plasmasheet for a magnetic storm, in which case, precursor substorm activity or a solar wind density enhancement would be a prerequisite. 1) Large solar wind Ey for an extended period ($>$1hr) saturates the tail electric field shielding. 2) This produces a strong cross-tail convection electric field. 3) A monoenergetic "nose" event penetrates deep into the magnetosphere from the (pumped up) plasmasheet. 4) Simultaneously a parallel electric field develops as the energetic nose event plasma dominate over the plasmaspheric cold plasma. 5) This parallel electric field extracts and energizes ionospheric plasma including H^+ and O^+. 6) Either the nose or the field-aligned plasma produce intense ICW which perpendicularly heat the beams and trap them in the magnetosphere. 7) When the convection switches off, the ring current is trapped and begins to decay through charge exchange.

Acknowledgements

This study was supported by NASA contract NAS5-30368 and NSF grant ATM-9458424. The authors gratefully acknowledge K. Ogilvie, E. Shelley, J. Dudeney, G. Rostoker, B. Blake and T. Fritz for the use of their data.

References

Blake, J. B. et al. CEPPAD: Comprehensive energetic particle and pitch angle distribution experiment on POLAR. In C. T. Russell, editor, *The Global Geospace Mission*, pages 531–562. Kluwer Academic Publishers, 1995.

Fennell, J. F., D. R. Croley, Jr., and S. M. Kaye. Low-energy ion pitch angle distributions in the outer magnetosphere: Ion zipper distributions. *J. Geophys. Res.*, *86*, 3375, 1981.

Gleisner, H., H. Lundstedt, and P. Wintoft. Predicting geomagnetic storms from solar-wind data using time-delay neural networks. *Ann. Geophys.*, *14*, 679–686, 1996.

Hamilton, D. C. et al. Ring current development during the great geomagnetic storm of february 86. *J. Geophys. Res.*, *93*, 14,343–14,355, 1988.

Kaye, S. M. et al. Ion composition of zipper events. *J. Geophys. Res.*, *86*, 3383–3388, 1981.

Lui, A. T. Y., D. J. Williams, E. C. Roelof, R. W. McEntire, and D. G. Mitchell. First composition measurements of energetic neutral atoms. *J. Geophys. Res.*, *101*, 1996.

Ogilvie, K. W. et al. Swe, a comprehensive plasma instrument for the wind spacecraft. In C. T. Russell, editor, *The Global Geospace Mission*, pages 55–77. Kluwer Academic Publishers, 1995.

Papitashvili, V. O. et al. Electric potential patterns in the northern and southern polar regions parameterized by interplanetary magnetic field. *J. Geophys. Res.*, *99*, 13,251, 1994.

Rostoker, G. et al. Canopus - a ground-based instrument array for remote sensing the high latitude ionosphere during the istp/ggs program. In C. T. Russell, editor, *The Global Geospace Mission*, pages 743–760. Kluwer Academic Publishers, 1995.

Sheldon, R. B. and D. C. Hamilton. Ion transport and loss in the earth's quiet ring current 1. data and standard model. *J. Geophys. Res.*, *98*, 13,491–13,508, 1993.

Shelley, E. G. et al. The toroidal imaging mass-angle spectrograph (TIMAS) for the POLAR mission. In C. T. Russell, editor, *The Global Geospace Mission*, pages 497–530. Kluwer Academic Publishers, 1995.

Smith, P. and R. Hoffman. Direct observations in the dusk hours of the characteristics of the storm time ring current particles during the beginning of magnetic storms. *J. Geophys. Res.*, *79*, 966, 1974.

Suzuki, A., M. Yanagisawa, and N. Fukushima. Anti-sunward space current below the magsat level during magnetic storms, and its possible connection with partial ring current in the magnetosphere. *J. Geophys. Res.*, *90*(B3), 2465–2471, 1985.

Whipple, Jr, E. C. The signature of parallel electric fields in a collisionless plasma. *J. Geophys. Res.*, *82*, 1525, 1977.

This preprint was prepared with the AGU LaTeX macros v3.1. File grl4 formatted 1996 October 1.