A New Magnetic Storm Model

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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 all aspects of a storm sequence, including ground, ionospheric and magnetospheric observations. 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 spatially narrow band of hot ions, compressed as it convects towards stronger B, can exceed the local cold electron density at the equator and thus generates a field-aligned space-charge potential that attempts to confine the hot ions to the equator. At some point on the field line, earthward of the equator, the growing cold electron density exceeds the hot ions and the potential is neutralized to approximately the electron thermal temperature, forming a double layer that extracts ionospheric ions. 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 structure is a dynamic balance between the current of corotating cold electrons and convecting hot ions, which would rapidly decay if it were not for the continuous power input of the convection electric field. When the 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. 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 a complete storm sequence. With a suitable inner tail model, we should be able to use only the solar wind density and electric field, $Ey = Bz \times Vx$, 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. On this day the Comprehensive Energetic Particle and Pitch Angle Distribution (CEPPAD) (*Blake et al.*, 1995) experiment detected two nearly monoenergetic bands superposed on the night side ring current (figure 1): a population of trapped ions at $\sim$90 keV, and a beam of field-aligned ions at $\sim$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. Since nose events are highly correlated with storms, and storms are defined by Dst, but Dst is generally not immediately available, we turn to the preliminary Dst provided by the Kyoto University web site. After subtracting the ionospheric Sq contribution using the "quietest day of the month" (April 7/8) method, we find a moderate storm of at least -63nT on the first hour of April 15. Additional support for the nose event identification 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 CU and CL 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

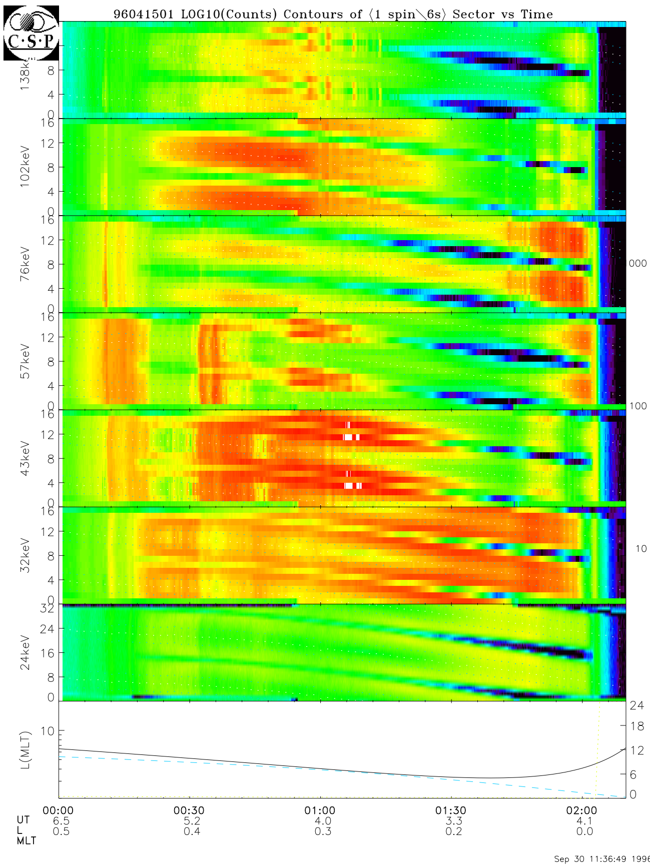

Figure 1: POLAR/CEPPAD/IPS data on April 15, 1996, displaying roll modulation of the counts in the 90° head in the energy bands from 24–138 keV. Dotted white and blue lines are 90° and 60° pitchangles.

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 at L>6 recorded very little activity, the riometer at L=4.4 as well 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 origin would 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 19, it found an anomalously large amount of O^+ in the ring current (RC) in two energy bands centered at 40 and 100 keV. Because of the short lifetime of O^+ against charge exchange, such a measurement is consistent with a storm injection occurring only a few days previously, since between storms, CAMMICE detects no O^+ enhancements. A similar storm on March 21 showed that the IPS zippers are simultaneous with the double peaked O^+ spectrum observed by CAMMICE. 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, a hot monoenergetic nose ion superposed on a cold plasmasphere electron population will produce a parallel electric field of several kT_e pointing away from the equator. That is, since a mirroring ion spends most of its time away from the equator, the electrons at the equator will experience a force pulling them toward higher latitudes. If the energetic ion density (or current density in a dynamic system) is greater than the plasmaspheric cold electron density, a second ion-dominated solution to the Whipple equations is possible that produces an ion space-charge potential at approximately the ion beam parallel energy. This space charge potential completely expels electrons from the equator and is only neutralized somewhere earthward on the flux tube where the cold electron density again exceeds the hot ions. At this point, the potential drops from kV to a few kT_e, forming a double layer. Naturally this space charge is shielded by neighboring flux tubes, generating a local perpendicular electric field that is manifest in the ionosphere by a "polarization jet" or a subauroral ion drift (SAID).

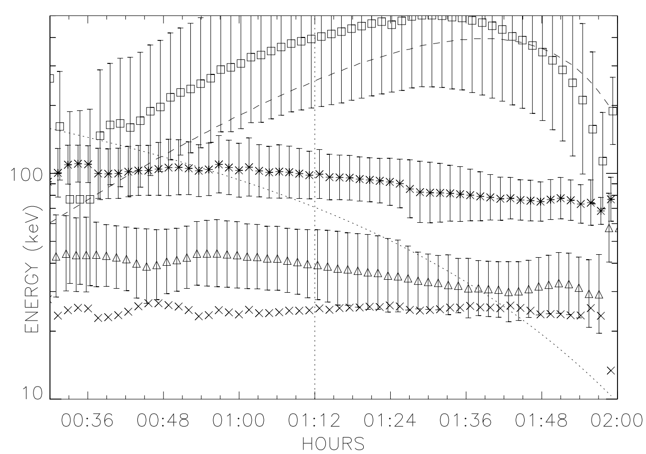

Figure 2: Peak fits to 96s averaged spectra of the 90° head. Ring current (□), nose ion (∗), beam ion (△) energies, and the ratio of nose/beam × 10 (×) are plotted. Error bars are FWHM from peak fits, since fitting errors are negligible. Overplotted with different scales are: the model equatorial magnetic 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.

By measuring the energy of these beams as the spacecraft crosses through this region, we can map out some features of this potential structure. We have fit the spectra with a sum of three peaks: a Chapman layer function appropriate for the ionospheric beam, a Gaussian for the nose ions, and a log-space Gaussian for the ring current ions. We note that an asymmetric Chapman layer function, $y = \exp(1 + x - \exp(x))$, is what one expects if the extraction potential is extended over some distance.

Figure 2 demonstrates how the three populations, beam, nose and RC, evolve during this orbit. The RC is adiabatically energized so that as the model equatorial magnetic field increases the energy increases, as noted by the squares and dashed line. A latitude effect is apparent due to the more rapid loss of low energy ions at higher latitudes. This energization is not seen by the nose ions because they are not an equilibrium trapped population, 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, and 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 beam energy is determined not 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 SAIDs which have been previously 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 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 subauroral 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 and Conclusions

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 RC, 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 RC (*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 RC. 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 RC amperage was observed in the partial RC. If we assume that half of the partial RC is carried by upward flowing ions, then we estimate that 1/6 - 1/8 of the total RC is composed of ions of ionospheric origin.

Thus we find that the mechanism described in the abstract not only provides a causal chain for the entire storm sequence, but has great predictive power in explaining many other observations not previously linked to storms.

Acknowledgements

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