Alfvén Boundaries: Noses and Zippers

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ABSTRACT

On April 15, 1996, POLAR was in a noon-midnight meridional plane and observed an atypical energetic particle distribution, characterized by a band of nearly monochromatic 90° ions at 60 keV, and a second, nearly monochromatic band of of field-aligned ions around 40 keV. These ions persisted from L=7-3.5. Below L∼3.5 the bands vanished, but reappeared as the spacecraft exited the magnetosphere. The upper band is identified as a "nose" event, first described by *Smith and Hoffman* (1974). The bimodal distribution is reminiscent of "zipper" events discussed by *Fennell et al.* (1981), though this may be the most energetic zipper event ever described. After examining the solar wind monitor and ground stations, we develop a scenario to explain this distribution, where the nose ions injected from the plasmasheet produce a parallel electric field that extracts oxygen from the ionosphere. Although we lack the Dst, we hypothesize that we were observing a classical ∼-100 Dst magnetic storm, albeit from a new perspective. We generalize this observation by proposing that all storm injections involve intense nose events that produce parallel electric fields that populate the ring current with ionospheric oxygen.

DATA ANALYSIS

The POLAR spacecraft is in a polar 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 inversely proportional to L-shell. 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) instrument detected an unusual distribution consisting of two monoenergetic bands of ions superposed on the night side radiation belt, and partially observed on the dayside (figure 1). Since the spacecraft was preparing to flip its axes, a maneuver intended to keep the auroral imagers in shadow and we supposed initially that we were seeing interference from hydrazine thrusters. However the thrusters had not fired, and on closer examination, the two bands showed all the characteristics of a monoenergetic beam of trapped ions at 60 keV, and a monoenergetic beam of field-aligned ions at 40 keV with a region of depleted plasma between the bands.

A monoenergetic beam is possible when a strong cross-tail electric field drives ions against the ∇B drift deep into the magnetosphere. That is, since the energy-dependent ∇B drift is clockwise and the energy-independent $E \times B$ drift is counter-clockwise, the only ions that can deeply penetrate are those whose energy is such that the two drifts nearly cancel. Such so-called "nose events" (*Smith and Hoffman*, 1974) must be nearly 90° trapped particles because of the adiabatic compression caused by the large increase in $|B|$ while convecting from the plasmasheet, which is the characteristic of the upper energy band in the data. Do we find any evidence for strong convection on April 14–15 that would support this hypothesis?

Examination of WIND data (*Olgivie 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 intense substorms with riometer absorption signatures at auroral latitudes. However the 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 effect 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 shed stress via substorms. The CANOPUS array detected a magnetic bay, a nearly equal response of AU and AL, suggesting that the current systems had moved equatorward, overhead of the magnetometers. Indeed, the Halley Bay magnetometer at L∼4

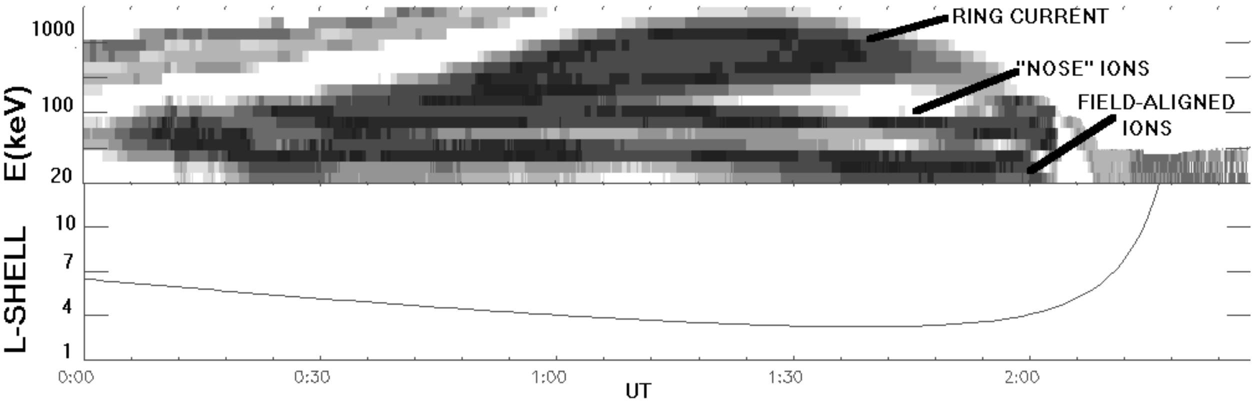

Figure 1: POLAR/CEPPAD/IPS ion "zipper" spectrogram taken on April 15, 1996.

(*Dudeney et al.*, 1995) showed a large H deflection with almost no Z deflection, indicative of strong overhead currents.

Ionospheric scintillations became very disturbed at this time as well. The IZMIRAN model *Papatashvili* (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 as the Halley Bay riometer at L$\sim$4, 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 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 Re, which POLAR/CEPPAD observed as a 60 keV band.

The monoenergetic field-aligned ions, however, are harder to explain. They have the wrong pitchangles to have convected from the plasmasheet, because the adiabatic decompression 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 in the magnetosphere, 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 mono-energetic, 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. What could this acceleration be?

Again, we recall that "zipper" events, *Fennell et al.* (1981) (identified first by *Kaye et al.* (1981)), had the same bimodal distributions. They found that the field-aligned low energy component was rich in O^+, and concluded that they were observing beams coming from the ionosphere. Since beams are seen at auroral latitudes, they supposed that their satellite, SCATHA, was on flux tubes connected to auroral arcs. Unfortunately the POLAR composition experiment, CAMMICE was turned off during this period, so we cannot verify this assumption for April 15. However when CAMMICE/MICS was switched back on, around April 20, it found a anomalously large amount of O^+ in the ring current. The only time for which CAMMICE/MICS observed more O^+, was March 21, 1996, which had a less well defined, but unmistakeable "zipper" distribution observed by CEPPAD/IPS. So we conclude that on April 15 we are observing O^+ ions accelerated to 30 keV by strong parallel electric fields in the ionosphere. Since these ions track $\sim$20 keV below the nose ions, it appears there must be a connection between them. What could be the connection between nose events and ionospheric beams?

(*Whipple*, 1977) and (*Chiu and Schulz*, 1978) argue that one can produce a field-aligned electric field if the electron and ion pitch angle distributions (PADs) are not identical. In this case, the ions mirror at a different location on the field line than the electrons, producing a double layer and strong parallel electric field. A nose event, because of its monoenergetic character at near 90° pitch angles, would produce just such a peculiar PAD. If the energetic particle density is comparable or greater than the plasmasphere, it seems

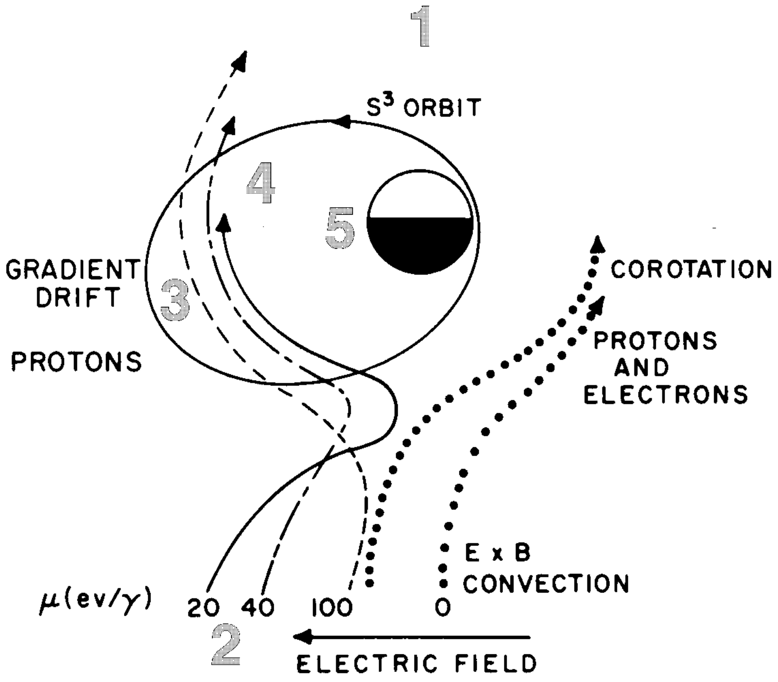

Figure 2: Schematic storm development. (1) IMF Ey exceeds some threshold for t>1 hr. (2) Cross-tail E-field develops when near-earth plasmasheet current systems saturate. (3) Convection drives a band of plasmasheet "nose" ions deep into the magnetosphere. (4) Parallel E-fields develop as nose ion densities dominate over plasmasheet electrons. (5) O^+ ions are drawn out of the ionosphere. (6) Ion-cyclotron waves scatter O^+ out of the loss cone, and they become trapped in the ring current.

likely that the inner magnetospheric plasma cannot neutralize the electric field by itself, but must extract ionospheric particles. Naturally the electric field created by this mechanism must be less than the energy content of the generating ions, so that this second band of ions remains at a distinct energy lower than the nose ions, in agreement with the observations. Such a parallel electric field also accelerates electrons down into the ionosphere to produce riometer absorption events. If the electric field is colocated with the nose plasma, the absorption must be a narrow strip in latitude, as seen in the CANOPUS data.

If this be the mechanism that generates field aligned electric fields and oxygen beams, then we have elucidated a new paradigm for magnetic storms. It is generally thought that magnetic storms are characterized by intense convection fields that bring plasmasheet plasma deep into the ring current. If this be true of all magnetic storms, then all storms should also create parallel fields and extract oxygen from the ionosphere. Thus models that attempt to predict Dst from solar wind parameters need to include this additional source of ring current plasma, which we expect to be a non-linear contribution. That is, big storms extract more oxygen than small storms, with a larger Dst effect.

Support for this theory, suprisingly came during the same COSPAR session where our paper was presented. M. Grande calculated the O^+/He^{++} ratio for the entire CRRES data set, about 14 months. He plotted this ratio versus Dst, and found a distinct linear trend; the larger the Dst, the larger the ratio, as we would predict. A second study by K. Mursula showed that the PC1 waves associated with ion-cyclotron waves (ICW) usually accompany storms. But during the most intense part of the main phase of a storm, the PC1 waves occurred primarily at dusk and the 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. T. Lui presented neutral atom composition measurements during a magnetic storm with GEOTAIL/EPIC data. The H and O spectra match nicely with the H^+ and O^+ spectra observed with AMPTE/CCE in a 1986 storm. 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. Thus this observation weakly supports our theory above as well. Finally, R. Horne addressed one weakness with this model, that ionospheric beams should mirror in the opposite ionosphere and be lost unless they scatter out of the loss cone. R. Horne presented wave growth studies showing that oxygen should be very unstable to waves that transversely heat the oxygen and trap it in the magnetosphere. These are the waves probably observed by Mursula, although Horne had modelled only one of two branches of the dispersion relation.

CONCLUSIONS

We have attempted to build a new paradigm 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 (fig 2): 0) It may be necessary to have a critical density plasmasheet for a magnetic storm, in which case, precursor substorm activity would be a prerequisite. 1) Bz <0 for an extended period (>1hr) saturates the tail and produces a strong cross-tail convection electric field. 2) A monoenergetic "nose" event penetrates deep into the magnetosphere. 3) Simultaneously a parallel electric field develops as the energetic nose event plasma dominate over the plasmaspheric cold plasma. 4) This parallel electric field extracts and energizes ionospheric plasma including H^+ and O^+. 5) Either the nose or the field-aligned plasma produce intense ICW which perpendicularly heat the beams and trap them in the magnetosphere. 6) When the convection switches off, the ring current is trapped and begins to decay through charge exchange.

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