Reflected solar wind ions and downward accelerated ionospheric ions during the January 1997 magnetic cloud event

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Abstract. On January 11, 1997, at 03:40:00 UT, while Polar was traveling up the dusk flank toward apogee, two ion instruments, TIDE and TIMAS, detected upflowing H^+ with an energy/pitch-angle dispersion resembling an ionospheric reflection of freshly injected solar wind ions. In the same region of space, TIDE and TIMAS observed cold beams of O^+ and H^+ traveling down the field line with equal bulk velocities. We interpret these ion signatures as concurrent observations of mirrored solar wind ions and downward accelerated ionospheric ions. By 03:42:00, an energy/pitch-angle dispersion of downward moving ions at very low energies was clearly evident in the TIDE data. This additional signature is interpreted as an indication of reconnection on the same field line in the southern hemisphere. We explain this unique combination of plasma distributions in terms of high-latitude reconnection and magnetic field line convection during northward-IMF conditions associated with the January 1997 magnetic cloud event.

Introduction

Magnetic reconnection was first proposed by *Dungey* [l961], assuming a southward interplanetary magnetic field (IMF). Two years later *Dungey* [1963] refined his reconnection model and included a northward-IMF reconnection scenario. In the thirty-five years since then, southward-IMF reconnection has been studied extensively, while northward-IMF reconnection has been studied to a much lesser extent. (See for example relevant papers in *Song et al*. [1995] and *Hultqvist and Øieroset* [1997].) A summary of northward-IMF reconnection models can be found in *Cowley* [1983], and a good review of global dynamics for northward-IMF was written by *Troshichev* [1990].

In this paper, we examine ion signatures observed during northward-IMF conditions associated with the arrival of an interplanetary magnetic cloud at the Earth. During the interval under study, on January 11, 1997, the Thermal Ion Dynamics Experiment (TIDE) and Toroidal Imaging Mass-Angle Spectrograph (TIMAS) on Polar detected four distinct ion populations when Polar was in the high-latitude dusk-side magnetosphere. One of these is reported here for the first time.

The first population detected (labeled population (I) throughout this paper) was a mantle-type distribution of upward flowing ions that was identified as solar wind H^+ injected at a northern reconnection site. This population showed the velocity distribution of magnetically reflected solar wind ions that was first reported by *Burch et al*. [1982]. The second population (II) observed was composed of upflowing ions associated with the cleft ion fountain [*Lockwood et al.*, 1985]. The third population (III) consisted of ionospheric H^+ and O^+ ions observed to flow down the geomagnetic field line with equal bulk velocities of about 70 km/s. The ultimate source of these ions is considered to be the cleft ion fountain with a subsequent acceleration in the reconnection region. The fourth population (IV) was downward flowing H^+ observed at very low energies with the energy/pitch-angle V distribution characteristic of velocity dispersion from a spatially or temporally localized source. Because of their low velocities of a few 10's of km/s, we believe that these are backstreaming magnetosheath ions injected in the southern hemisphere reconnection region [*Fuselier et al.*, 1997]. Table 1 summarizes these four plasma populations.

Table 1. Plasma Populations Observed by TIDE and TIMAS on January 11, 1997

	Origin	Species	Energy Range or Velocity	Description
I	Magnetosheath	H^+	50-500 eV	Upfloing mirrored V's
II	Ionosphere	O^+	10-20 eV	Upflowing cleft ion fountain
III	Ionosphere	H^+,O^+	70 km/s	Downflowing accelerated cleft ion fountain with equal bulk velocities
IV	Magnetosheath	H^+	10-40 eV*	Downflowing V's Backstreaming in the magnetosheath flow
				* The energy range of population (IV) V's at 03:43:00 UT

The TIDE and TIMAS Instruments

In this study we use two ion instruments on the Global Geospace Science (GGS) Mission Polar spacecraft to observe ions in the energy range from spacecraft potential to 32 keV. TIDE [*Moore et al*., 1995] measures ions in the energy range from spacecraft potential to 500 eV. The instrument uses an electrostatic mirror/retarding potential analyzer system to provide differential energy analysis. In the total-ions mode, TIDE uses seven polar detectors combined together in a 157.5° fan opening from the spacecraft spin axis. The spacecraft sweeps this field of view to cover 96% of 4[pi] steradians in one spin period.

TIMAS [*Shelley et al*., 1995] is a first-order double focusing imaging spectrograph that simultaneously measures all mass-per-charge components from 1 to 32 amu over a nearly 360° by 10° instantaneous field-of-view. TIMAS sweeps out almost a 4[pi] steradian solid angle image in half a spin period (3 s). The energy range covered is 15 eV to 32 keV.

Observations

On January 11, 1997, during an interplanetary magnetic cloud event, the Wind spacecraft was located 94 R_E upstream of the Earth in the solar wind. The IMF measured by the Magnetic Field Investigation on Wind [*Lepping*, *et al*. 1995] turned northward just after 21:00 UT on January 10, and, aside from a brief southward turning around 03:00 UT on January 11, (unobserved by the Magnetic Field Investigation on IMP-8, which was located in the solar wind just upstream of the bow shock on the dusk flank) remained northward until after 05:30 UT on January 11, 1997.

During this time, the Polar spacecraft was traveling in a dusk-dawn orbit. At 03:40:00 UT, Polar was over the auroral oval (4.9 R_E, 17.6 MLT, 70.9 InvLat) in a region of trapped hot plasma. As Polar traveled up the dusk flank toward apogee, three different plasma populations were observed by TIDE and TIMAS: (I) upflowing ions that exhibited an energy/pitch-angle dispersion resembling an ionospheric reflection of freshly injected ions, (II) a cleft ion fountain population, and (III) a downward flowing ion population whose source was identified as the Earth's ionosphere. Later a fourth population (IV), consisting of injected solar wind ions at very low energies was observed flowing downward in the northern hemisphere.

Figure 1 shows the TIDE observations of these four populations. Using the mass discrimination of TIMAS (Fig. 2), the ions in Figure 1 can be identified by species. The mantle-type H^+ distribution (I) covers the energy range from 50 eV to 500 eV. This population exhibits an energy pitch-angle dispersion which is seen as a mirrored (upside down) V in Figure 1 (higher energy ions are seen traveling upward along the geomagnetic field line (180° pitch angle), while lower energy particles are seen traveling upward at smaller pitch angles). The highest observed energy/charge of the mirrored V's is 500 eV, the maximum observable energy for TIDE. The mirrored V's that are seen in the TIDE spectrogram in Figure 1 can also be seen as mirrored V's in the upper panel of the TIMAS spectrogram in Figure 2, indicating that these are H^+ ions. A weaker lower energy upward flowing field-aligned population (II) of ions was also present and is consistent with the cleft ion fountain described by *Lockwood et al*. [1997] (Fig. 1).

The unique new features shown in Figures 1 and 2 are the downward flowing ionospheric ions (III).

In an energy range similar to population (I), downward flowing O^+ ions were observed, while at lower energies (a few 10's of eV) a strongly field aligned downward flowing population of H^+ was seen. These cold beams of O^+ and H^+ observed traveling down the field line are found to have equal bulk velocities of 70 km/s. We interpret these ions as cleft ion fountain particles which have been accelerated to a common velocity (rather than a common energy) in the reconnection process, as described by *Cowley* [1982] for southward-IMF conditions.

Two minutes later, at 03:42:00 UT, the low energy, small pitch-angle portion of the reflected H^+ distribution (I) was still seen by TIDE (Fig. 1). The downward traveling O^+ and H^+ (III) were also still seen by TIDE. However, in addition, a very low energy V, which evolved over several minutes, was clearly seen by this time traveling down the field line (IV). This population shows the energy/pitch-angle signature of injected ion velocity dispersion [*Burch et al*., 1982]. Because of their very low energies (down to 10 eV), these ions are identified as originating in a southern hemisphere reconnection region where a fraction of the ions have thermal velocities that cause them to backstream in the magnetosheath flow as described by *Fuselier et al*. [1997].

Interpretation and Discussion

One possible reconnection scenario that would explain the observed ion signatures is shown in Figure 3. In this scenario, we have a northward-IMF where reconnection occurs in both polar regions, although not simultaneously. Reconnection first occurs over the northern cusp (point A in the diagram). The reconnected field line convects sunward and reconnects again in the southern hemisphere (point B). Finally, the newly closed field line is convected around the dusk-side of the Earth toward the night-side.

The direction of the plasma flow is shown in Figure 3a. At the northern reconnection point, solar wind ions will have access to geomagnetic field lines and will begin flowing into the cusp. Ionospheric ions that had been traveling up the geomagnetic field lines will be accelerated at the reconnection point and will either continue up the reconnected field line or will be reflected back toward the ionosphere. At the southern reconnection point, most of the solar wind ions will travel tailward. However, a high thermal velocity component of the distribution will have sufficient parallel velocity to travel back up the field line toward the northern hemisphere, as described by *Fuselier et al*. [1997]. Southern hemisphere ionospheric ions will be accelerated at the reconnection site and will either be reflected back to the southern ionosphere, will travel back toward the tail, or will be travel up toward the northern hemisphere.

This reconnection/plasma flow scenario is found to be consistent with the observations and identification of the ion sources:

1. The hot trapped plasma seen in the TIMAS data (Fig. 2), perpendicular velocities on the order of 5-10 km/s, and a run of the magnetospheric model TH-93 [*Toffoletto and Hill*, 1993] all indicate closed field lines at the spacecraft location for the observed IMF and solar wind conditions.
2. The upward flowing ion signatures seen at 03:40:00 (I) are consistent with mirrored solar wind ions injected onto the field line at the northern reconnection site.
3. The strongly field-aligned H^+ and O^+ population seen at 03:40:00 (III) is consistent with an ionospheric source. The downward flows and elevated energies of several tens to a few hundred eV for O^+ suggest acceleration at the high-latitude magnetopause by a northward-IMF reconnection region, with the acceleration imparting a common velocity (rather than a common energy) increment [*Cowley*, 1982].
4. The travel time from the northern reconnection site to the spacecraft should be the same for the mirrored solar wind ions (I) and the downward accelerated ionospheric ions (III). Using a dipole field approximation at the spacecraft location, a first order check of the proposed scenario gives a transit time of approximately 15 minutes. This time is consistent with the convection time of a field line from noon to dusk.
5. The fact that the H^+ ions seen at 03:42:00 (IV) had minimum energies as low as 10 eV suggests that they originated in the southern hemisphere, where the high energy tail of the solar wind ion distribution is able to backstream toward the northern hemisphere, as described by *Fuselier et al*. [1997].
6. Comparing the slopes of the energy/pitch-angle dispersions of populations (I) and (IV) at 03:42:00 shows that these are two distinct populations. The higher slope for the low energy V's (IV) indicates that

this population was injected onto the field line at a higher altitude than the higher energy V's (I) [*Burch et al.*, 1982]. This comparison suggests these populations were injected onto the field line at two distinct locations, which is consistent with the proposed scenario of reconnection in both the northern and southern hemispheres.

Conclusions

This is the first time concurrent observations of reflected solar wind ions and downward accelerated ionospheric ions have been seen. We believe this is direct evidence of northward-IMF reconnection, with the associated injection of solar wind and reflection of ionospheric ions at the reconnection site. The Polar spacecraft, located below the reconnection point, observed these particle signatures after the field line had convected to the dusk flank and the faster moving solar wind ions had reflected off the ionosphere.

We believe the lower energy V's seen clearly by 03:42:00 are further evidence of reconnection on the same field line in the opposite hemisphere. A similar feature has been seen by *Fuselier et al.*, 1997, for southward-IMF conditions.

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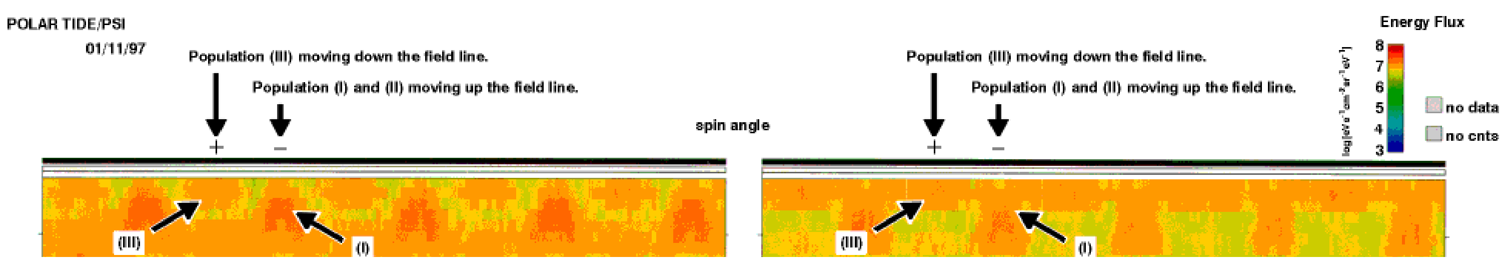
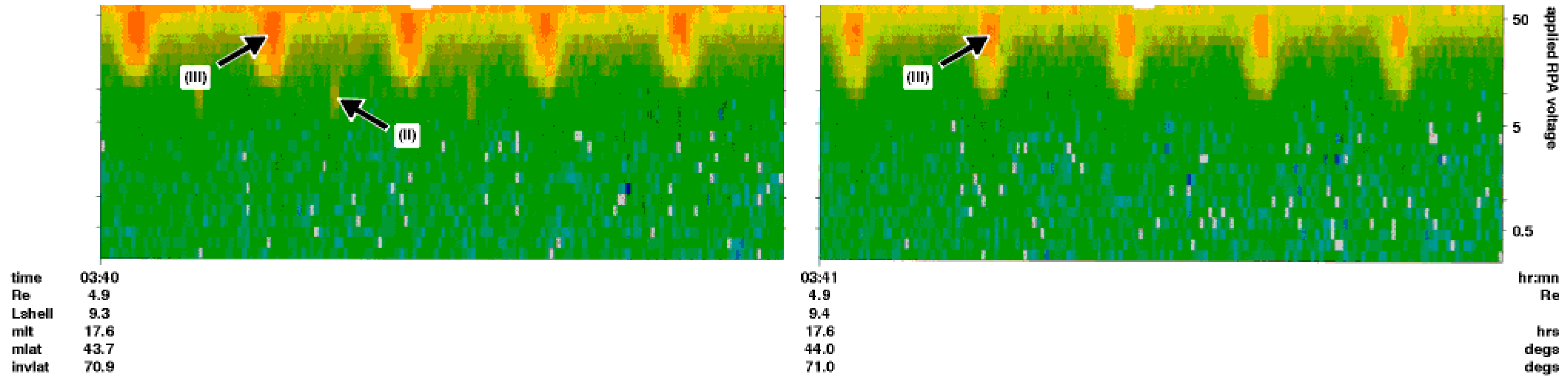




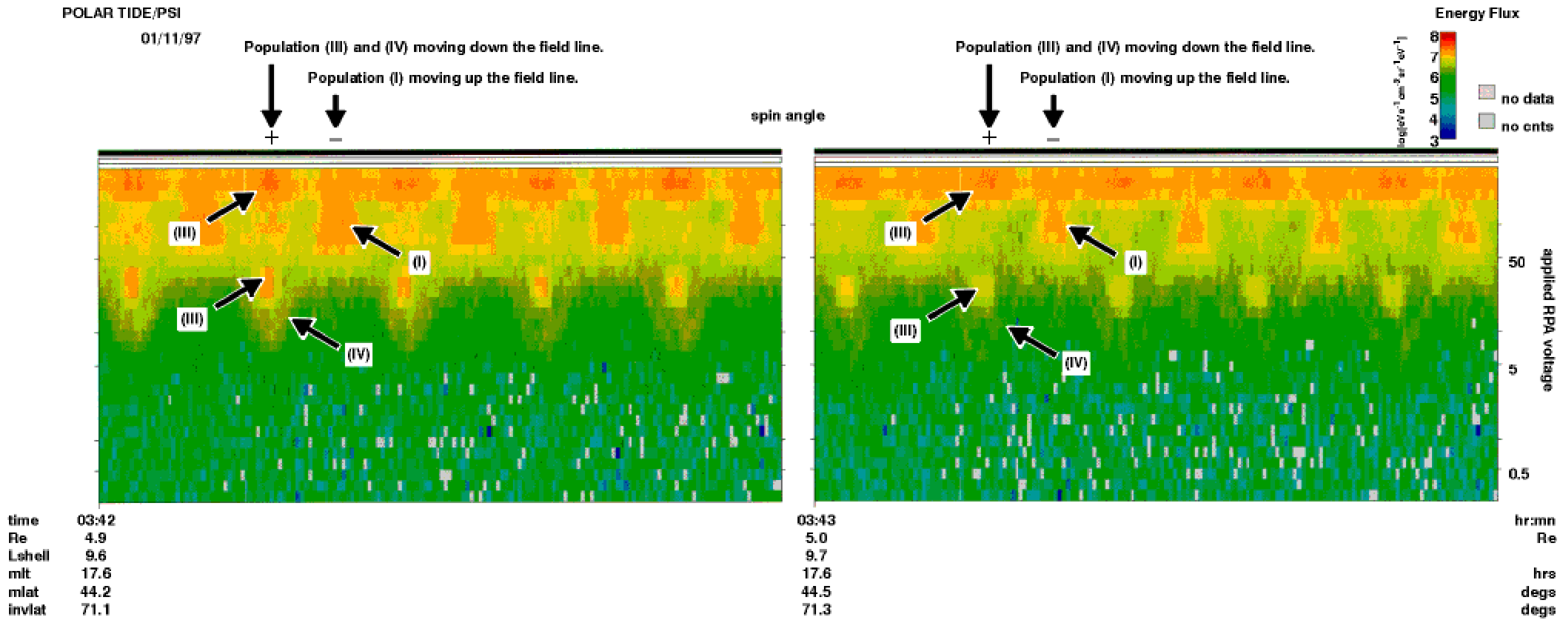
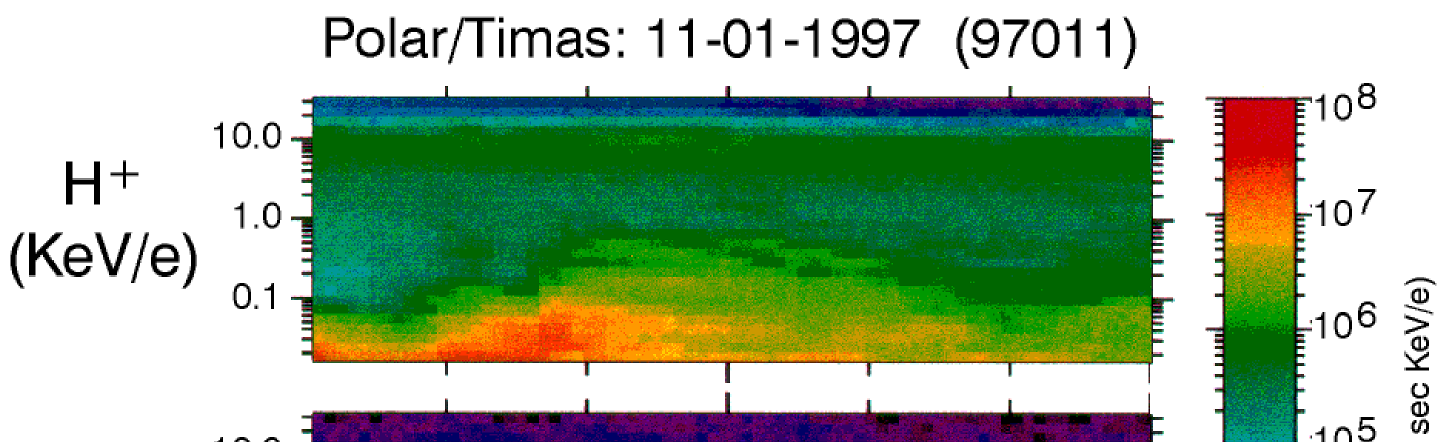


Figure 1. A TIDE energy-time spectrogram showing all species for four thirty-second time intervals from 03:40:00 to 03:43:30 on January 11, 1997, with spin angle along the horizontal axis. Each thirty-second interval shows five separate spins. The positive magnetic field direction is indicated by the +, which indicates that the particles are traveling down the field line in the northern hemisphere, and the negative field direction by the -, which indicates particles are traveling up the field line. Populations (I) - (IV) and the magnetic field direction are indicated for the second spin in each interval.



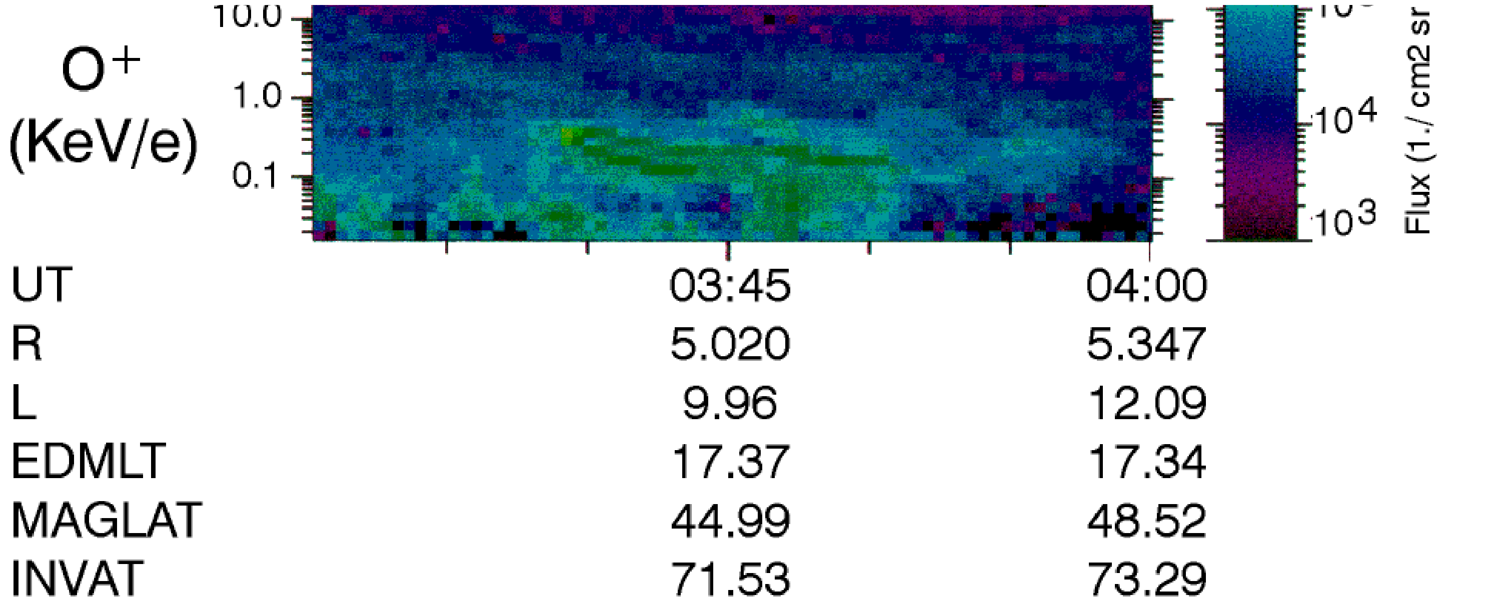
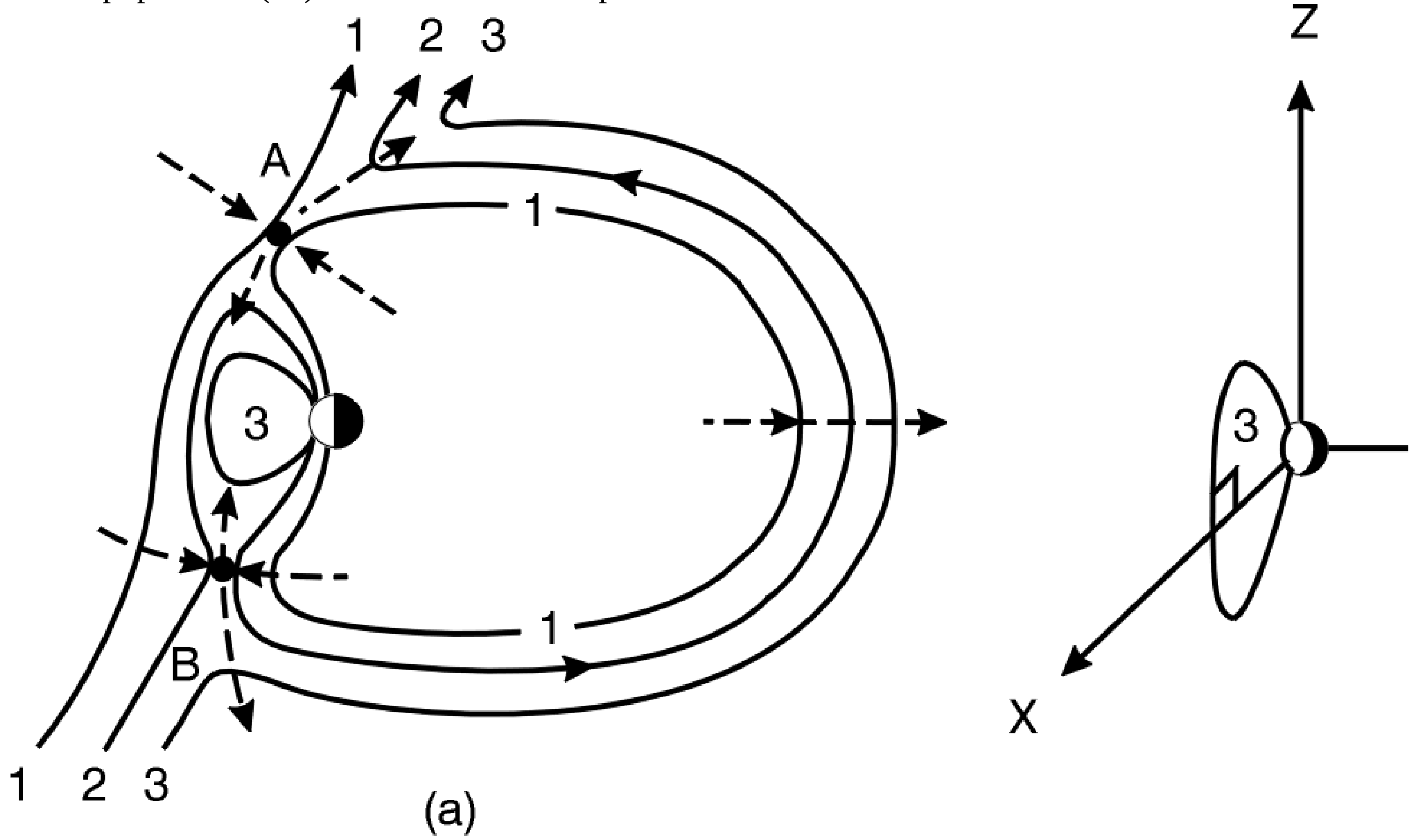
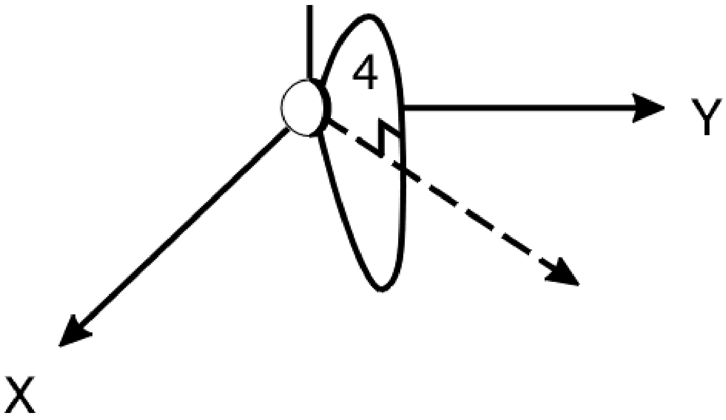


Figure 2. A TIMAS energy-time spectrogram showing H^+ (upper panel) and O^+ (lower panel) for the time interval of 03:40:17 to 03:40:41 UT on January 11, 1997. The pitch angle is plotted between the two panels, with 0º indicating particles traveling down the field line and 180º degrees indicating particles traveling up the field line. An upward directed energy/pitch-angle dispersed H^+ population (I) and downward traveling field aligned H^+ population (III) are seen in the upper panel. A downward field aligned O^+ population (III) is seen in the lower panel.





(c)

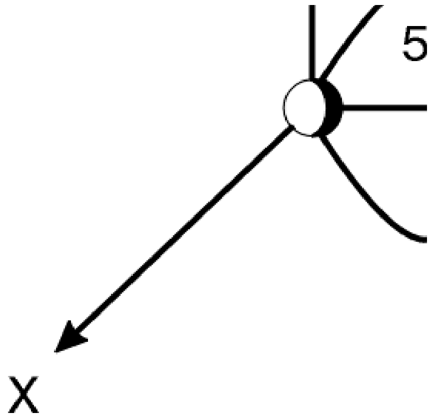


Figure 3. A northern-IMF reconnection scenario in which the numbers indicate the field line sequence. In (a), the dot indicates the location of the neutral line, and the arrows indicate the direction of convection in the vicinity of the neutral line [from *Cowley*, 1983, Figure 8(b)]. (b)-(d) indicate the convection of the field line from noon to dusk.