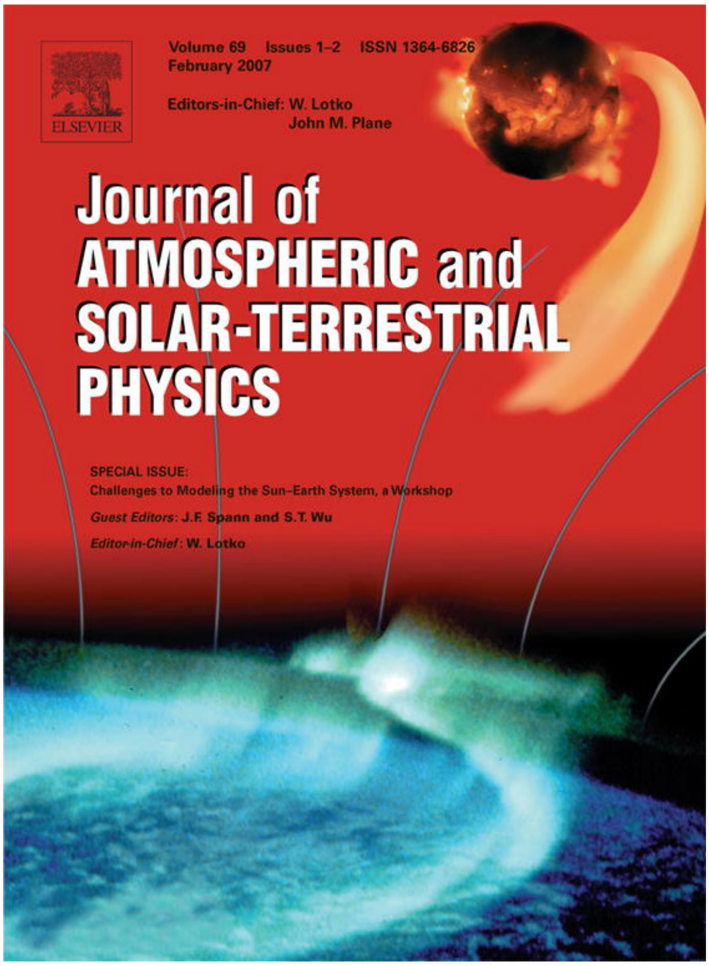
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Geospace activity dependence of cold, streaming ions in the near-Earth magnetotail

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Abstract

Results from a survey of the occurrence statistics of cold, streaming ion observations in the magnetotail lobes (lobal wind) in the Polar TIDE database are presented, considering lobal wind observation occurrence percentages during quiet and active times in geospace. It is found that lobal winds are observed more than half the time, even during magnetic storm conditions, and in quiet times they are seen nearly three-quarters of the time. They are seen throughout the magnetotail portion of the Polar orbit (apogee ~9 R_E near the magnetic equator in the tail during the survey epoch), and are regularly measured at all local times and at all latitudes within the surveyed domain. The beams flow along the magnetic field away from the ionosphere, and are often seen as bi-directional streams at lower magnetic latitudes, indicating that they are present on closed field lines as well as open ones. The commonness of these cold, streaming ions emphasizes the need for global magnetospheric modelers to account for this population.

Keywords: Ionospheric ions; Geomagnetic activity; Ionosphere–magnetosphere coupling

1. Introduction

The contribution of the ionosphere to the magnetospheric supply of plasma has been studied for decades (e.g., Dessler and Michel, 1966; Shelley et al., 1972; Horwitz, 1982; Moore and Delcourt, 1995). H^+, He^+ and O^+ have all been observed streaming out of the high-latitude ionosphere into the polar cap region (e.g., Moore et al., 1997; Strangeway et al., 2000). They have been seen in the tail lobes (e.g., Sharp et al., 1981; Seki et al., 1998) and in the plasma sheet (e.g., Peterson et al., 1981; Orsini et al., 1990). Energetic O^+ is also a big contributor to the ring current, particularly during large magnetic storms (e.g., Hamilton et al., 1988; Daglis et al., 1993).

The existence of ionospheric plasma in the near-earth magnetotail is not well understood. The high-latitude regions of the lobes above the polar caps have been surveyed (e.g., Moore et al., 1997; Su et al., 1998; Elliott et al., 2001), and the low- to mid-latitude range of the near-Earth lobes across the nightside magnetosphere has just recently been studied (Liemohn et al., 2005). This latter study presented a survey of cold, streaming ion observations (lobal wind) as seen from the Polar spacecraft,

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when apogee was near the magnetic equatorial plane. Their conclusion was that these streams are present much of the time, with every orbit in the surveyed database seeing at least a brief interval of this ionospheric-origin ion population.

The Liemohn et al. (2005) study showed several plots relating the fraction of orbit time against several geophysical parameters. Nearly all of the plots showed the same trend: during active times, uni-directional stream observations go up while bi-directional stream observations go down. The present study extends this concept by examining occurrence percentages for various subsets of the surveyed database from Liemohn et al. (2005). This study addresses the question of whether the streams are truly a common feature of the magnetosphere during active times. In the discussion section, the question of how much global magnetospheric modelers should care about this population is pondered.

2. Polar TIDE observations

2.1. Lobal wind survey of the Polar TIDE database

Since its launch in 1996, the apogee of the Polar satellite has been processing southward (Acuña et al., 1995). By the second half of 2001, its 9 R_E apogee was very close to the magnetic equator on the nightside, offering regular latitudinal sweeps through the near-Earth magnetotail. The thermal ion dynamics experiment (TIDE) onboard Polar measures low-energy (0–373 eV) ions (Moore et al., 1995), and during this 6-month interval TIDE routinely observed cold beams flowing along the magnetic field, both away from and towards Earth. This feature appeared to be quite regular in the data, and Liemohn et al. (2005) presented a statistical study of the occurrence rates for these lobal winds.

The survey conducted by Liemohn et al. (2005) included all usable TIDE orbits from July 1, 2001 to December 31, 2001 inclusive. All data recorded between -60° and $+60^\circ$ magnetic latitude during the ascending node of the orbit (that is, at high altitudes near apogee) were included. This resulted in over 2000 hours of usable TIDE observations. Using well-defined criteria for the identification of the ion streams in the spectrogram plots, each 15 min interval of this data was assigned one of three labels: uni-directional lobal wind, bi-directional lobal wind, or no lobal wind observation. Various geophysical and solar wind parameters were then correlated with these occurrence rates. The main conclusion of the Liemohn et al. (2005) study is that these cold ion streams are ubiquitous, being observed 70% of the time in the surveyed database.

2.2. Example case studies

Fig. 1 shows a typical example of a uni-directional lobal wind observation (in energy flux) after a thick plasma sheet crossing (August 14–15, 2001). The division between thick and thin plasma sheet crossings is defined at 1 h for the full reversal of the magnetic field x component. For the Polar spacecraft at apogee, this translates into roughly 1 R_E of distance, mostly in the z-direction. The magnetosphere was very quiet during this interval, with Dst above zero throughout the interval, and near zero for several days around it. It is seen in the spin–time spectrogram (upper left plot) as a narrow band that tracks one of the magnetic field look directions, in this case, the negative B-field direction. Because these data are from the northern hemisphere, this beam is flowing downtail, away from the ionosphere. In the energy–time spectrogram (lower left plot), it is seen that the energy flux peaks above 100 eV for this stream. Liemohn et al. (2005) showed that the phase space density peaks well within the energy range of the TIDE instrument (up to 373 eV). The peak energy flux intensity is usually greater than $10^7\,\mathrm{eV}\,(\mathrm{s\,cm^2\,sr\,eV})^{-1}$. The lobal wind observation appears to come and go throughout the orbit, a common feature of the lobal wind measurements. It abruptly ends near 04:45 on August 15, where a different, lower-energy population centered on the spin angle of the spacecraft ram direction is seen at higher latitudes. Note that the plasma sheet crossing is just before the selected interval, and the high-latitude pass as Polar approaches perigee is just after it.

The plots on the right-hand side of Fig. 1 show the moments of the lobal wind stream for the same interval. These values were numerically calculated within a restricted region of velocity space to extract the moments only for the cold ion stream. Specifically, the summation was performed over energies above 10 eV and only inside of a 90°-spin angle width centered around the bin looking along the negative B-field direction. The rough indicator of lobal wind observations is when $V_x > 100\,\mathrm{km\,s^{-1}}$ with $V_y \sim 0$, and $T_{\|} \sim T_{\perp}$ in the 20–50 eV range.

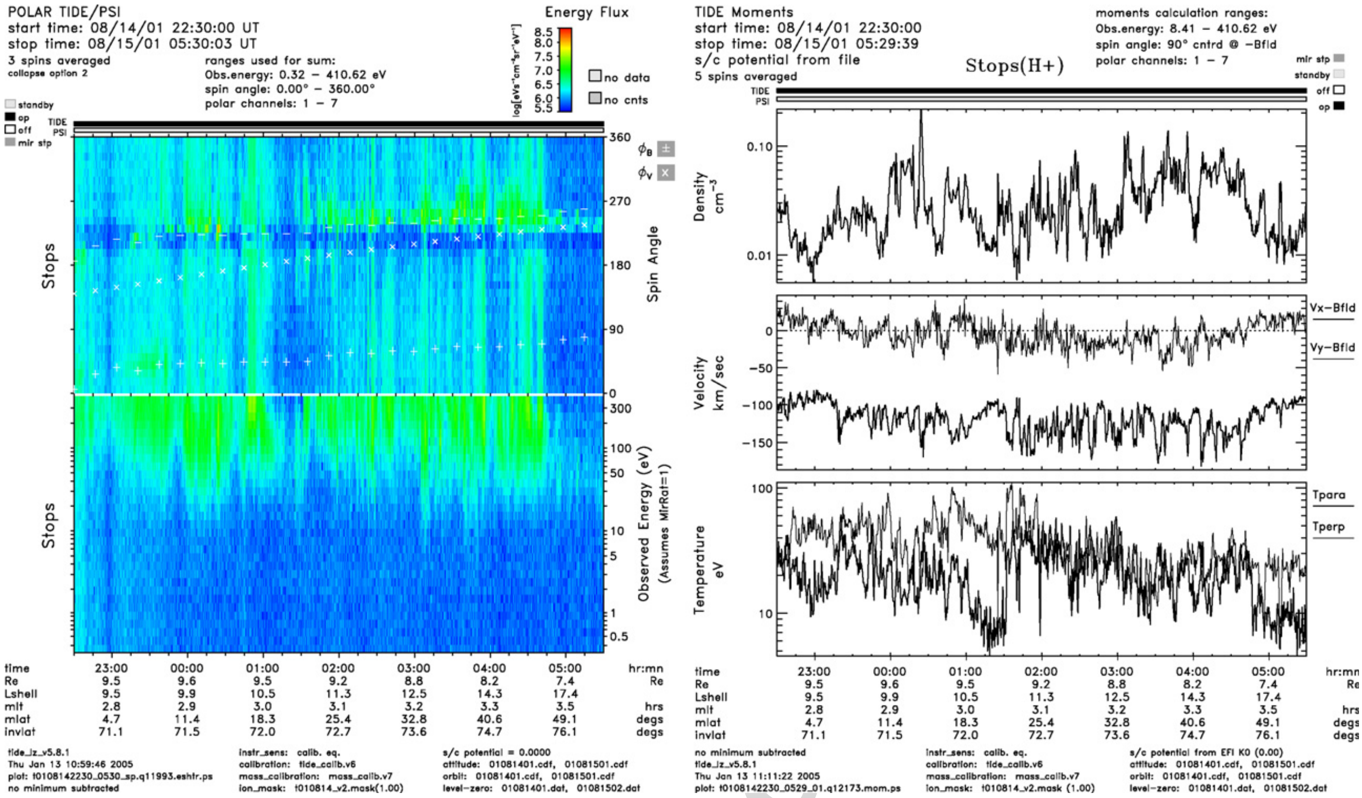

Fig. 1. Spectrograms (left-hand side) and moments (right-hand side) from the Polar TIDE instrument during an orbit on August 14–15, 2001. This is an example of a thick plasma sheet crossing. The moments are calculated in a restricted region of velocity space: a 90°-spin angle track following the local negative B-field direction and energies above 10 eV.

For this interval, the temperature plot is the best indicator of lobal wind observations. Liemohn et al. (2005) showed example moments of lobal winds ranging from 0.1 to 1.0 cm^{-3}. For this interval, the lobal wind density ranges from 0.02 to 0.2 cm^{-3}.

Fig. 2 shows an example observation of a unidirectional wind observation after a thin plasma sheet crossing. These observations are on October 22, 2001, during an intense magnetic storm. The lobal wind observations are much more intense during this interval than the quiet time interval shown in Fig. 1, with energy fluxes reaching 3×10^8 eV (s cm^2 sr eV)$^{-1}$ at times. The lobal wind measurements are interspersed with measurements of a colder ion population centered on the spin angle of the spacecraft ram direction (a population usually seen only at high latitudes). There is a clear step between these two populations; they do not appear to be co-located. While both are almost certainly of ionospheric origin, their mutual exclusivity implies that they come from different source regions.

Fig. 2 also shows the lobal wind moments during this active-time interval (again, summed over a restricted velocity space region around the beam). In these plots, both the velocity and the temperature anisotropies are good indicators of when the lobal wind was observed (rather than the other ionospheric population). The lobal wind densities are significantly higher than in Fig. 1, ranging between 0.03 and 1.0 cm^{-3}. This is not a new result; enhancements in ionospheric-origin ion densities in the magnetosphere have been seen before during both storms (e.g., Lennartsson et al., 1981; Nosé et al., 2003) and substorms (e.g., Daglis and Axford, 1996; Nosé et al., 2001).

Note that in both Figs. 1 and 2, the ions were assumed to be entirely H$^+$ in the calculation of the moments values. If all of the ions are actually O$^+$, then the density will be 4 times larger and the velocities will be 4 times lower than those shown.

A full analysis of the lobal wind moments is beyond the scope of this paper. These two examples are shown here to give an understanding of the range of densities, velocities, and temperatures for this magnetospheric population. These values should be kept in mind when interpreting the occurrence statistics presented below. In particular, it should be noted that the velocity and temperature values do not change significantly from quiet to

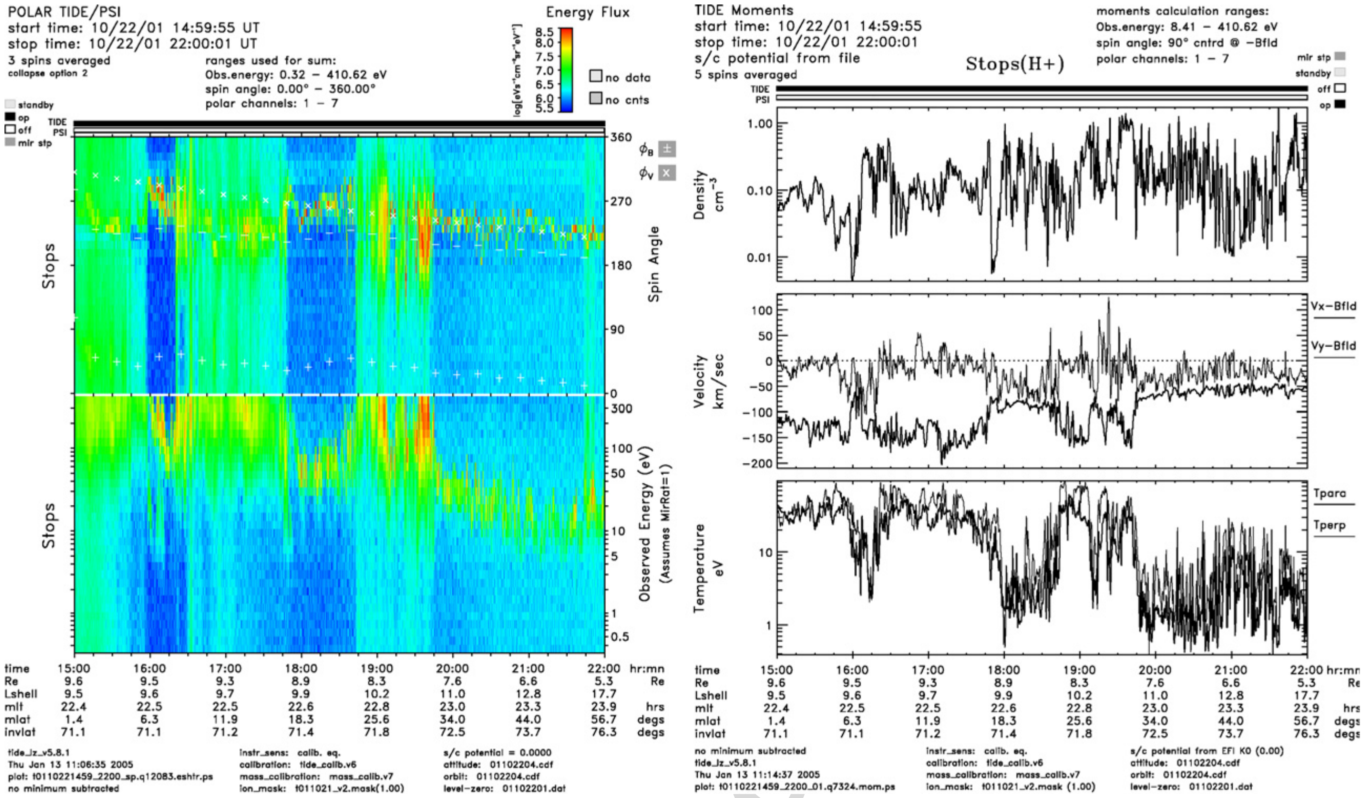

Fig. 2. Spectrograms (left-hand side) and moments (right-hand side) from the Polar TIDE instrument during an orbit on October 22, 2001. This is an example of a thin plasma sheet crossing. The moments are calculated in a restricted region of velocity space: a 90°-spin angle track following the local negative **B**-field direction and energies above 10 eV.

active times, but the density can increase by up to an order of magnitude.

2.3. Occurrence statistics

Table 1 shows a few occurrence percentages for TIDE lobal wind observations during the second half of 2001. Each row represents a different categorical subset of the database. The 4 columns give total hours of observation in that subset, followed by the percentage of those hours in which uni-directional wind was observed, in which bi-directional wind was recorded, and in which either uni- or bi-directional wind was seen (columns 2–4, respectively). There are 5 groupings of subset categories, as indicated by the headings within Table 1. Three different activity parameters are used to sort the database. The first is whether there was a thick or thin plasma sheet crossing during the orbit, with the former indicating a quiet time and the latter implying a more active magnetosphere. The thick and thin definitions are those given above. The second parameter is the average Dst during the half orbit, which is an indicator of storm and non-storm intervals. For this study, a dividing value of −40 nT was selected to split the data between these 2 categories. The third is the *z*-component of the interplanetary magnetic field (IMF Bz), which is an indicator of energy coupling and transfer from the solar wind to the geospace. The dividing value for this parameter was −2 nT.

The reader is encouraged to cogitate on these numbers and consider their various ramifications. A few highlights will be mentioned here. The first is that, when unsorted by activity parameter (Dst or IMF Bz), lobal winds are seen roughly 70% of the time. The percentage goes up a bit during quiet times, and correspondingly down during active times. None of the numbers in the final column, however, are below 50%. Even during active times, lobal winds are a common feature of the near-Earth magnetotail. This trend was not particularly evident in the Liemohn et al. (2005) results, because they did not categorize the orbits according to Dst or IMF Bz value.

Another important result of Table 1 is the change in uni-directional and bi-directional wind observations from quiet to active times. In general, the quiet time subsets have lower uni-directional wind percentages (relative to the entire database value) and

Table 1
Occurrence percentages for cold, streaming ions in the near-Earth magnetotail

	Hours	Uni-dir wind	Bi-dir wind	Either wind
All Dst values, all IMF Bz values				
Entire database	2211.5 h	30.1%	40.3%	70.4%
Thick plasma sheet orbits	1791.75	26.5	44.6	71.1
Thin-plasma sheet orbits	419.75	45.6	21.7	67.4
Only half-orbits with $Dst < -40\,nT$				
Either plasma sheet orbits	261.0	27.3	29.1	56.4
Thick plasma sheet orbits	173.5	20.6	37.9	58.5
Thin-plasma sheet orbits	87.5	40.6	11.7	52.3
Only half-orbits with $Dst > -40\,nT$				
Either plasma sheet orbits	1950.5	30.5	41.8	72.3
Thick plasma sheet orbits	1618.75	27.1	45.3	72.5
Thin-plasma sheet orbits	332	47.0	24.4	71.3
Only half-orbits with IMF $Bz < -2\,\mathrm{nT}$				
Either plasma sheet orbits	460.75	36.5	29.9	66.4
Thick plasma sheet orbits	314.25	30.7	35.0	65.7
Thin-plasma sheet orbits	146.5	49.0	18.9	67.9
Only half-orbits with IMF $Bz > -2\,nT$				
Either plasma sheet orbits	1750.75	34.0	46.5	71.4
Thick plasma sheet orbits	1477.5	25.6	46.6	72.3
Thin-plasma sheet orbits	273.25	43.8	23.2	67.1

higher bi-directional wind percentages. In general, the active time subsets show the opposite trend. The notable exception to this rule is that, when organized by Dst, all of the occurrence percentages drop. It appears that during magnetic storm times (as indicated by Dst), TIDE observed fewer/shorter intervals of lobal winds relative to non-storm times. However, a comparison of Figs. 1 and 2 reveals an example of increased lobal wind densities during a magnetic storm. It is unclear at this time, then, whether the total amount of plasma is more or less during storms, or indeed during any active time. A detailed analysis of the lobal wind moments will be the focus of a forthcoming study.

3. Summary and Discussion

A survey of the occurrence statistics of lobal wind observations in the Polar TIDE database has been conducted for the second half of 2001, when Polar's ~9 R_E apogee was near the nightside magnetic equatorial plane. The initial findings of this survey were reported by Liemohn et al. (2005). This study extends that survey by considering the occurrence percentages during quiet and active times in geospace. It was found that lobal wind is observed more than half the time, even during magnetic storm conditions, and in quiet times they are seen nearly three-quarters of the time. These cold, streaming ions from the ionosphere are, therefore, quite common in the near-Earth magnetotail. They are seen throughout the magnetotail portion of the Polar orbit, and are regularly measured at all local times and at all latitudes within the surveyed domain. The beams flow along the magnetic field away from the ionosphere, and are often seen as bi-directional streams at lower magnetic latitudes, indicating that they fly through the plasma sheet. Assuming that the ions are H^+, their typical density ranges from 0.1 to 1.0 cm^{-3}, parallel velocity is usually between 100 and 200 $\mathrm{km\,s}^{-1}$, and parallel and perpendicular temperatures of 20–50 eV.

The name of the Huntsville 2004 Workshop, "Challenges to Modeling the Sun-Earth System", inclines the authors to end this study by posing a challenge to global magnetospheric modelers. These lobal winds represent a major source of plasma to the tail. It is not simply flying out anti-sunward never to pass near the Earth again, but the bi-directional flows imply that these particles exist on closed as well as open field lines. Such a significant plasma population should be included in numerical simulations of geospace. For proper inclusion in such models, it will be necessary to develop a reasonable ionospheric boundary condition for these particles. Several studies address this boundary condition issue (e.g., Strangeway et al., 2000; Huddleston et al., 2005), while others have examined the source region of these particles (e.g., Winglee, 2003; Moore et al., 2005). Proper acceleration mechanisms must also be included to match the observed velocities and temperatures of these lobal winds. An open question is whether multi-fluid calculations are required to accurately simulate the influence of these ions through on the magnetosphere. That is, the particles of solar and ionospheric origin might necessitate separate but coupled equations of motion. Two questions come to mind: (1) Are the moments similar between the particles of solar and ionospheric source? (2) Are the "regions of dominance" for each source distinct? (That is, are there no large regions where the densities are comparable?) If the answer to either of these questions is no, then perhaps multi-fluid calculations are needed.

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