Low-energy (order 10 eV) ion flow in the magnetotail lobes inferred from spacecraft wake observations

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[1] Cold ionospheric ions with eV energies are common in the magnetosphere and can travel far out in the magnetotail. However, they are difficult to measure with conventional ion spectrometers mounted on spacecraft, since the potential of a sunlit spacecraft often reaches several tens of volts. In this paper we present two alternative methods of measuring the cold-ion flow with the Cluster spacecraft and apply them on one case in the magnetotail at 18 Rs. 1. Ion spectrometer in combination with artificial spacecraft potential control; 2. Deriving ion flow velocity (both perpendicular and parallel) from electric field instruments. The second method takes advantage of the effect on the double-probe instrument of the wake formed behind a spacecraft in a plasma flow. The results from the two methods show good agreement and are also consistent with polar wind models and previous measurements at lower altitudes, confirming the continuation of low-energy ion outflows.


1. Introduction

[2] Cold ions with kinetic energies of a few to tens of eV are injected into the terrestrial magnetosphere through ion outflow processes from the ionosphere. From theoretical estimates supported by observations in combination with simulations, Chappell et al. [1987, 2000] have shown that the ionospheric outflows could be the dominant source of plasma supply to the magnetosphere.

[3] Cold plasma of ionospheric origin is therefore common in the magnetosphere, including the magnetotail lobes. However, due to the very low densities in the lobes, the spacecraft potential, $V_{sc}$, usually is several tens of volts positive, so that ions below the corresponding energy in eV cannot reach the onboard particle detectors. When the ions are accelerated to energies above $eV_{sc}$, for example, by the plasma motion of the Pc 5 wave events observed with Geotail [Hirahara et al., 2004], or by convection and associated centrifugal acceleration, they become visible on board spacecraft. In the tail, this has allowed a wealth of investigations like the plasma sheet injection studies using data from ISEE [Orsini et al., 1990], Geotail [Seki et al., 2002] and Cluster [Sauvaud et al., 2004] data, to mention just a few: the reader is referred to these works for further references.

[4] While there thus is a substantial literature concerning the flow in the magnetotail of cold ions with a total energy above about 50 eV, relatively little is known about the population at very low energies, around a few tens of eV or less. Special circumstances sometimes allow such ions to be seen. Early measurements with the ISEE spacecraft [Etcheto and Saint-Marc, 1985] found an “anomalously” high plasma density in the plasma sheet boundary layer revealed by a relaxation sounder. Since then, other event studies have provided evidence of what Olsen [1982] termed the “hidden” cold-ion population in the geomagnetic tail. Seki et al. [2003] reported very low-energy ions in the deep tail plasma sheet observed on the Geotail spacecraft. At the time of observation the spacecraft was in eclipse, resulting in a negative spacecraft potential allowing ions at any energy to reach the detectors on the satellite. Nevertheless, only by artificially regulating the potential of the Polar satellite has it been possible to gather significant statistics on ions at or below a few tens of eV, presented by Moore et al. [1997] and Su et al. [1998] in their studies of ionospheric cold plasma flows out to 8 Rs. To our knowledge, no study has been able to establish the flow properties of ions below some 50 eV further out than the Polar apogee at 8 Rs.

[5] In this paper we present a case study of cold ions in the magnetotail with Cluster. The protons are so low in energy that they are only detectable with the onboard ion spectrometer CIS when the artificial spacecraft potential control (ASPOC) is activated, and even then most of the population is hidden from CIS. However, these ions can simultaneously be indirectly detected with the electric field instruments, EFW and EDI, from the wake formed behind another of the four Cluster spacecraft. We first show evidence for cold-ion flows in both ion and electric field data, and then derive the flow properties from these data.

2. Analysis of Particle Data

[6] CIS consists of two different instruments: the mass-separating instrument CODIF, which was used in this study, and the hot-ion analyzer, HIA [Rème et al., 2001]. Figure 1 shows CODIF data from spacecraft 3 (henceforth denoted SC3) collected during 1 hour, when the Cluster spacecraft
The distribution function for $H^+$ is the magnetic field projected in the $Torkar et al.$ cut in the $R$ plane for $v_z = 0$. The distribution function has been corrected for the spacecraft potential of 7 V, since CODIF measures the energy of the ions relative to the spacecraft potential. From Figure 3 we see that the hydrogen flow is aligned with the magnetic field, and has a velocity of 40 km/s (corresponding to 9 eV flow energy).

The oxygen flow has too high an energy to be measured by CODIF on SC4 (in RPA mode), and was therefore determined from the distribution function on SC3. After correction for the 40–60 V spacecraft potential, we obtained a flow velocity with an anti-sunward component of around 30 to 35 km/s ($v_y$ is not reliable due to anode problems on SC3, and we therefore disregarded this component; and $v_x$ fluctuates around 0 km/s).

3. Analysis of Electric Field Data

Evidence of cold flowing ions can also be found in electric field data from SC3 for the same event. Cluster carries two instruments for measurements of electric fields using different techniques: the double-probe instrument EFW [Gustafsson et al., 1997] and the electron drift instrument EDI [Paschmann et al., 1997]. The difference between the EDI and EFW data, which can be seen in Figures 2c and 2d, is due to a potential created in a wake behind the spacecraft.

A wake will form behind a spacecraft for supersonic ion flows, that is, $W_i > KT_i$, where $W_i$ is the bulk ion flow energy and $KT_i$ the thermal energy. If, in addition, the plasma is sufficiently tenuous, the spacecraft potential will exceed the ion flow energy, resulting in $eV_{sc} > W_i > KT_i$. This creates an enhanced wake, since in this case the ions are deflected by the potential structures around the spacecraft [Eriksson et al., 2006]. For Debye lengths greater than the spacecraft dimensions the wake can be significantly enlarged, as has been verified by particle-in-cell simulations [Engwall, 2004; E. Engwall et al., Wake formation behind...
positively charged spacecraft in flowing tenuous plasmas, submitted to *Physics of Plasmas*, 2006]. Figure 4 shows schematically the wake formation in supersonic flows. In the case of an enhanced wake the ion density will be largely depleted behind the spacecraft. The ion wake will, to a large extent, be filled with subsonic electrons, creating a negative potential in the wake. The EFW probes, which are mounted on 44 m wire booms (probe-to-probe separation 88 m), will observe this negative potential, while the keV electron beam from EDI is unaffected.

The wake can provide the plasma flow speed through the application of a simple model. We assume that the ions are unmagnetized on the wake length scale, so that the wake field measured by EFW is in the flow direction. Then $E^w = E^{EFW} - E^{EDI} = gu$, where $u$ is the flow velocity and the scalar $g$ may be a function of, for example, $V_s, T_i$, and the flow speed $u$, but should be independent of the flow direction. Decomposing the components of $u$, we obtain:

$$E^w = gu_\perp + gu_\parallel \frac{B}{B}$ (1)

where $u_\perp$ is known from EDI data, $u_\parallel = E^{EDI} \times B/B^2$. Since $E^w$ has two measured components, we have two equations for the two unknowns $g$ and $u_\parallel$: $g = \frac{(B \cdot E^w)}{E^{EDI}} = \frac{B E^w - B E^{EDI}}{E^{EDI}}$ $u_\parallel = \frac{E^{EDI} - E^w}{B}$ (2)

When calculating $g$ special care has to be taken for values of $E^{EDI}$ approaching zero. In the analysis, we have removed the points for calculated values of $g$ and $u_\parallel$ where $E^{EDI} < 0.05$ mV/m.

[13] We cannot apply our model to electric field data from SC4 for this event, since ASPOC reduces the spacecraft potential below the ion flow energy, thereby removing the wake. Instead, we used the electric field data from SC3 (Figures 2c and 2d), giving an anti-parallel velocity ranging between approximately 20 and 30 km/s (see Figure 5b).

[14] The perpendicular drift velocity is the same for all ion species, when the “frozen-in” condition applies. While the parallel velocity of different ion species should be the same if centrifugal acceleration is dominating [Cladis, 1986], other energization processes may lead to parallel velocity depending on particle mass. In this case, $u_\parallel$ must be interpreted as a weighted average of the parallel velocities of the different particle species. The weighting will be in favour of the lighter species since they are more affected by the spacecraft potential due to their lower energy and hence more effective for creating the wake. In a case like in Figure 1, where the oxygen ions are sufficiently energetic to reach the ion detectors on the spacecraft, they obviously do not contribute to the wake and the derived $u_\parallel$ in (2) is the parallel velocity of the protons.

[15] The parallel flow velocity derived from the electric fields should therefore be compared to the H$^+$ velocity from CODIF on SC4. It is not possible to compare the two methods on the same spacecraft, as either $V_s$ is low, so that the ions can be measured by the particle detectors, but no wake is formed, or $V_s$ is high, in which case we can derive the flow velocity from the wake observed by the electric field instruments, but the ions are prevented from reaching the CODIF detectors. Comparing the two derived velocities from SC3 and SC4 (Figure 5c), we see that the mean value and the size of the variations show good agreement, although details of course differ between the two spacecraft.

4. Discussion and Conclusions

[16] We have used Cluster data to study the cold plasma in the northern lobe of the terrestrial magnetotail for one event using two different methods. One method employs a particle detector, CODIF, whose range of accessible energies was extended down to around 7 eV by using the artificial spacecraft potential control ASPOC. Only when ASPOC was activated, and by running the CODIF detector in RPA mode, it was possible to measure the cold flowing protons. The cold flowing O$^+$ ions with much higher energy...
could also be detected on the Cluster satellites where ASPOC was not operating.

[17] The other method we developed to study the cold ion flow at locations where it is inaccessible to ordinary particle instruments exploits the fact that a wake forms behind a spacecraft in a supersonic ion flow, and that this wake can be observed by the double-probe electric field instrument EFW. The electron drift instrument EDI observes the unperturbed electric field, and the two instruments together can then provide the direction of the wake, and hence of the flow. We can also calculate the full flow speed, including its parallel component. Comparison to the flow derived from particle data shows very good agreement.

[18] As the wake method only works in situations where the flowing ions are deflected by the spacecraft potential before reaching the spacecraft and hence cannot be detected by a particle detector, it is intrinsically impossible to use the two methods simultaneously on the same spacecraft. However, thanks to the particular configuration of the Cluster spacecraft (ASPOC activated and CODIF in RPA mode on SC4, ASPOC off and EDI on for SC3) in this particular event, it was possible to compare the results of the two methods on two different spacecraft. Events where such a comparison can be made are rare: in fact, we found only a couple of other events when scanning the complete Cluster database of the tail lobes beyond 5 RE, from June 2001 through September 2004, where the instrument setup as well as the geophysical setting (presence of low-energy ions) was suitable. Nevertheless, the presented event is sufficient to establish that the new method of cold plasma flow detection by observation of the spacecraft wake actually works, and that it can be used in future studies.

[19] The flow measurements obtained with both methods at 18 RE are in accordance with the polar wind flow properties measured using the Polar satellite at 8 RE by [Su et al., 1998], although our event appears to show an unusually high oxygen flow speed. Geotail was used to observe cold plasma in the central plasma sheet at and beyond our location at 18 RE, and above. The event is the first velocity measurement of low-energy plasma flows beyond 8 RE, while we cannot directly measure the ion temperature, the fact that a wake is observed shows that the ion flow is supersonic, so that the temperature must be below the flow kinetic energy. As the derived drift speed of 20–40 km/s in Figure 5 corresponds to a proton flow energy of 2–8 eV, the proton temperature must be on the order of 1 eV or less for a wake to be created. Plasmas with these low temperatures could only originate from the ionosphere and we thus show the continuation of the cold ionospheric outflows studied by Su et al. [1998] at 8 RE to at least 18 RE.

[20] Our main conclusions are:

[21] 1. Low-energy (order 10 eV) ion outflows with general properties as observed at 8 RE in previous studies extend to at least 18 RE.

[22] 2. Data from double-probe and electron drift instruments can be combined with a simple model for the wake behind a spacecraft to estimate the flow velocity (magnitude and direction) of a tenuous, supersonic plasma flow.

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References


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