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A statistical study on O^+ flux in the dayside magnetosheath

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Abstract. Studies on terrestrial oxygen ion (O^+) escape into the interplanetary space have considered a number of different escape paths. Recent observations however suggest a yet insufficiently investigated additional escape route for hot O^+: along open magnetic field lines in the high altitude cusp and mantle. Here we present a statistical study on O^+ flux in the high-latitude dayside magnetosheath. The O^+ is generally seen relatively close to the magnetopause, consistent with observations of O^+ flowing primarily tangentially to the magnetopause. We estimate the total escape flux in this region to be $\sim 7 \times 10^{24}\,\mathrm{s}^{-1}$, implying this escape route to significantly contribute to the overall total O^+ loss into interplanetary space.

Keywords. Magnetospheric Physics (Magnetosheath)

1 Introduction

Ionospheric outflow in Earth's polar cap occurs on open field lines and is therefore the most likely source of atmospheric origin to escape into the solar wind. One of its main constituents is oxygen ions (O^+). The motion of the upflowing plasma is governed by magnetospheric processes and interactions between the magnetosphere and the solar wind. When studying these interaction mechanisms, a study of O^+ is preferable, since H^+ of ionospheric origin can be difficult to distinguish from H^+ of magnetosheath origin, which enters the magnetosphere along the open magnetic field lines of the cusps. Inflow of solar wind plasma into the cusps provides not only particles but also electromagnetic plasma waves, effective in heating and accelerating the upflowing ionospheric plasma (see, e.g., André et al., 1997; Waara et al., 2011; Slapak et al., 2011). Ions that reach the high altitude magnetosphere above the polar cap have been energized sufficiently to overcome gravity and are flowing along field lines leading downstream in the magnetotail.

O^+ in the magnetotail lobes is observed as cold beams (Seki et al., 1998; Liao et al., 2010). The cold beams are an effect of velocity dispersion (Horwitz, 1986), where a combination of perpendicular convection and differences in parallel velocity separate the tailward-streaming ion populations into narrow velocity distributions. Tailward-streaming ions will convect to the tail plasma sheet or (if the parallel velocity is high enough) pass the neutral point and be lost. Haaland et al. (2012) modeled the motion of low energy and cold ions with parallel velocities typically around 25–30 $\mathrm{km\,s^{-1}}$, and concluded that their fate was strongly dependent on the convection speed, mainly driven by dayside reconnection.

Nilsson et al. (2012) presented observations of spatial distributions of O^+ ions and wave activity in the high altitude polar cap. The efficient heating in the cusp leads to high O^+ temperatures and parallel velocities ($> 100\,\mathrm{km\,s^{-1}}$) in the high altitude cusp/mantle. This region is also where the strongest fluxes are observed, and the high parallel velocities will cause the majority of this plasma to escape into interplanetary space. The escape does not necessarily have to take place in the distant magnetotail after passing the neutral point, but may flow across the magnetopause into the magnetosheath along open field lines. A case study of O^+ in the dayside magnetosheath was presented by Slapak et al. (2012). They concluded that the ions had escaped along open magnetic field lines directly from the cusp/mantle, and they showed that this escape route is possible if the upflowing ions are heated sufficiently in the cusps.

Studies on O^+ escape into the dayside magnetosheath have been reported, and both flow along open field lines and finite gyroradius effects have been suggested as feasible escape mechanisms. Observations of O^+ in the dayside magnetosheath during storm conditions were presented by Zong and Wilken (1998) and Zong et al. (2001), who suggested the ions to be of ring-current origin, and referred to both flow along open field lines and finite gyroradius effects as possible escape mechanisms. Dayside observations of O^+ escape close to the equatorial plane correlated with a northward IMF were reported by Kasahara et al. (2008), who showed that the escape took place along open field lines in relation to reconnection processes. Hirahara et al. (1997), Marcucci et al. (2004) and Taktakishvili et al. (2007) are other examples of observations and studies of O^+ escape. Seki et al. (2001) reported that the total flux of O^+ in the magnetotail lobes decreases with distance, and argued that this property was due to convectional transport into the plasma sheet and subsequent return flux to the lower latitude ionosphere. They estimated the total O^+ loss rate (including escape in the tail lobes, via plasmoids, and leakage of plasma sheet and ring-current ions through the dayside magnetopause) to be $\sim 5 \times 10^{24}\,\mathrm{s}^{-1}$. However, they did not consider direct O^+ escape along open magnetic field lines from the cusp/mantle into interplanetary space, which the studies of Slapak et al. (2012) and Nilsson et al. (2012) indicate can be significant and therefore worth investigating. Studies of polar cap/cusp O^+ flows have been performed by several authors (Abe et al., 1996; Yau and André, 1997; Lennartsson et al., 2004; Nilsson, 2011) who all estimated a total outflow flux of the order $\sim 10^{25}\,\mathrm{s}^{-1}$. The total O^+ flux in the near-Earth tail (0–75 R_E) was estimated by Seki et al. (2001) to be $1.8 \times 10^{24}\,\mathrm{s}^{-1}$. This is much smaller than the total fluxes observed in the cusps, and the difference may be caused by significant direct escape of O^+ into the magnetosheath.

In this paper we present a statistical study of oxygen ions in the dayside magnetosheath, in order to estimate a total O^+ flux and determine whether this escape route is significant or not. To be able to perform this study, two main issues had to be considered: the considerable amount of contamination of the O^+ data due to intense H^+ fluxes and the sometimes non-trivial task of distinguishing magnetosheath data from magnetospheric data. The latter was done by visual inspection of dayside magnetopause crossings. To avoid significant contamination from intense magnetosheath H^+ flows we considered only O^+ ions with energies > 3000 eV. The process of making the magnetosheath data set is discussed in Sect. 2.1.

2 Measurements

The data used in this statistical study are obtained by the composition distribution function (CODIF) spectrometer onboard Rumba, spacecraft 1 in the Cluster mission (Escoubet et al., 2001). A brief presentation of the instrument will be given, followed by a description of the magnetosheath data set used for the O^+ flux analysis.

The CODIF instrument provides ion composition data in the energy-per-charge range 40 eV e^{-1} to 38 keV e^{-1}. It uses a time-of-flight technique and can resolve the major magnetospheric ion species with an energy and angular resolution of $\mathrm{d}E/E \approx 0.16$ and 22.5°, respectively. The CODIF instrument is described in more detail by Rème et al. (2001).

2.1 The data set

The data set we use in this study was obtained by the Cluster spacecraft and covers the high-latitude dayside magnetosheath during January to May (2001–2003), when the Cluster formation had an apogee at the dayside (19 R_E), and passed through the high-latitude magnetosheath, cusp and mantle two times per orbit. The identifications of the magnetopause crossings have been made manually. A magnetopause crossing is often clearly seen as distinct changes in different physical quantities (Paschmann et al., 1978), where the most profound one often is a sudden change of the magnetic field direction. The H^+ density is a strong indicator as well, since the density (a few tens of cm^{-3} in the magnetosheath) quickly decreases to much lower values (typically of the order $1\,\mathrm{cm}^{-3}$ or smaller) in the magnetosphere. The same behavior is observed for the ratio of the plasma pressure over magnetic pressure (β); in the magnetosheath $\beta \approx 1$, but it decreases quickly to values that are several orders of magnitude smaller in the magnetosphere. For the cases where a distinct magnetopause could not be determined, we picked data from a point where we were sure that the satellites were positioned in the magnetosheath. Based on that, the typical magnetosheath characteristics were fulfilled in the observed plasma.

The magnetosheath data set was then visually inspected for high energy O^+ (> 3 keV). The reason for a lower energy limit is to avoid contamination of the O^+ data when intense proton fluxes are present. From inspection it is clear that significantly heated and accelerated O^+ ions reach particle energies up to at least 38 keV (the maximum energy per charge to be measured by CODIF), whereas the magnetosheath protons seldom reach energies above 3 keV; see, e.g., the case study presented by Slapak et al. (2012). Therefore, an O^+ set containing ions of energies > 3 keV is assumably unaffected by the intense proton fluxes, whereas a low energy subset (< 3 keV) is strongly contaminated. This condition is confirmed when correlating the proton fluxes with the fluxes of high and low energy O^+ respectively. There is a clear correlation between the H^+ flux and the low energy O^+ flux for the magnetosheath data. A similar correlation cannot be seen when high energy O^+ flux is compared to the H^+ flux. Also, if the O^+ data are contaminated, a peak at $v_\perp(O^+)/v_\perp(H^+) = 1/4$ would be expected (Nilsson et al., 2006). This property is not seen; on the contrary $v_\perp(O^+)$ is in general similar to but somewhat larger than $v_\perp(H^+)$. These statistical characteristics of the magnetosheath data confirm the assumption that the set of high energy O^+ is not effected by contamination.

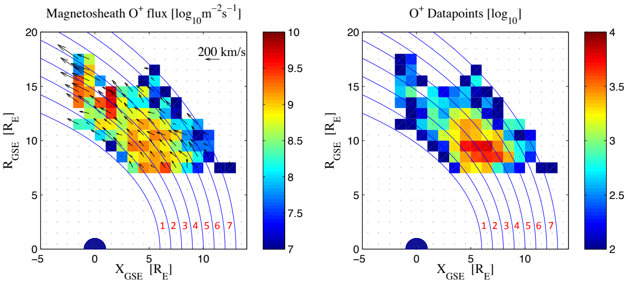

Fig. 1. Left: average O$^+$ escape flux in the magnetosheath, given in cylindrical GSE coordinates. The flux (m^{-2} s^{-1}) is given by a color scale, and the bulk velocity (magnitude and direction) is given by black arrows. In the top right corner an arrow's length defines the velocity corresponding to 200 km s^{-1}. The eight blue lines divide the magnetosheath data set into seven segments (numbered 1–7) with a width of $\sim 1\,R_E$. The lines are theoretical magnetopauses cutting the X_{GSE}-axis at 6, 7, …, 13 R_E. Right: the spatial distribution of the of the data set is shown.

3 Observations

Figure 1 (left) shows the flow of high energy O$^+$ (> 3 keV) observed in the high-latitude magnetosheath. We use a cylindrical reference frame with X_{gse} and $R_{gse} = (Y_{gse}^2 + Z_{gse}^2)^{1/2}$ as spatial coordinates. Each bin is a $1 \times 1\,R_E$ square, for which mean values for the flux and bulk velocity have been calculated. No O$^+$ was observed further out in the magnetosheath than indicated in the figure, although many hours of magnetosheath data were available. The mean direction of the flow and the magnitude of the bulk velocity are given by black arrows, centered in each bin. An arrow in the upper right corner of the figure defines the length corresponding to 200 km s^{-1}. Each square bin is designated with a color defining the average escape flux of that particular bin. The flux values are defined by the logarithmic color bar to the right in the same figure, and the escape flux of a particular bin is defined as the average flux of observed O$^+$ in that bin times the O$^+$ occurrence rate in the magnetosheath of that bin. The occurrence rate of each bin is defined as the number of data points where O$^+$ is observed in the magnetosheath divided by the total number of data points. The occurrence rate is needed to calculate the total O$^+$ escape flux in the magnetosheath. This will be further discussed below. Figure 1 (right) gives an overview of the spatial distribution of the O$^+$ magnetosheath data set, which contains a total of nearly 100 000 data points. The majority of the measurements is obtained in a region where each bin typically contains a few thousand data points and where most of the considered spacecraft trajectories are. The rest of the bins (where magnetosheath O$^+$ is observed) contain a few hundred data points each, sufficient for a statistical analysis.

The blue lines in Fig. 1 are theoretical magnetopauses (Shue et al., 1997), used to divide the magnetosheath data set into spatial segments, numbered 1 to 7, such that Segment 1 is the one closest to Earth. The binning of the data is made with no consideration to an actual distance to the magnetopause because of the large variation of its position. Many observations of O$^+$ have been made up to several hours after crossing the magnetopause, leaving us with no control of the magnetopause position at the given measurement points. A total of 85 % of the recorded magnetopause crossings take place within Segments 2, 3 and 4. As it turns out, these segments will contribute most to the total flux calculation. Magnetopause crossings are however experienced in all of the segments, reflecting the high variability of the magnetopause position.

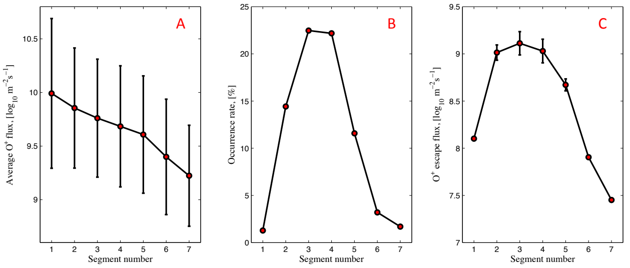

Fig. 2. **(A)** Average flux, **(B)** magnetosheath O$^+$ occurrence rate, and **(C)** O$^+$ escape flux (average flux times occurrence rate), as functions of outward distance, with Segment 1 and 7 corresponding to the innermost and outermost segment respectively.

The spatial segments defined in Fig. 1 have been used to investigate the characteristics of the O$^+$ flux in the outward direction relative to Earth. The results are demonstrated in Fig. 2. Plot a shows the average O$^+$ flux of each segment, with error bars indicating one standard variation. There is a clear trend that the measured fluxes in general decrease with the distance from Earth. The decrease from Segment 1 to Segment 7 is about one order of magnitude (10^{10} to 10^9 m^{-2} s^{-1}). This result could give the impression that the closer the segment is to Earth, the more it contributes to the total magnetosheath flux, but this is not true. As mentioned above, Fig. 2A shows the average O$^+$ fluxes when O$^+$ is observed, and thus we also have to take into account how often we observe O$^+$ in the magnetosheath for the particular segments. For this cause we calculate the occurrence rate for each segment i by $N_i(\mathrm{O}^+)/N_{\mathrm{tot},i}$, where $N_i(\mathrm{O}^+)$ is the number of data points in segment i for which magnetosheath O$^+$ is observed, and $N_{\mathrm{tot},i}$ is the total number of data points in segment i. The result is shown in Fig. 2b. The highest occurrence rates (~ 22 %) are within Segment 3 and 4. Segment 1, where the highest average flux is observed, has on the other hand very low occurrence rate (~ 1 %). For the most outward segments, the occurrence rate drops quickly to just a few percent. Even further out the occurrence rate becomes zero, since no O$^+$ was observed there. Multiplying the results in Fig. 2a and b segment by segment yields the average escape flux, F_i, of each segment i (Fig. 2c). Due to the low occurrence rates of the outermost segments, we now get

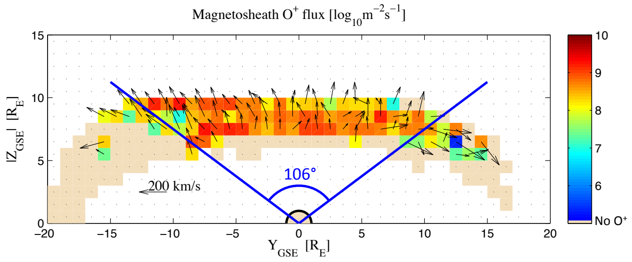

Fig. 3. The escape flux in the YZ_{GSE} plane, showing the spatial distribution of our measurements. The observed O^+ flux is given by the color scale to the right, ranging from 10^5–$10^{10}\,m^{-2}\,s^{-1}$. Regions colored in beige correspond to regions where measurements have been taken place but no O^+ has been observed. The black arrows correspond to the YZ-component of the average flow velocity. The majority of the observed significant escape fluxes are within an angular extent of 106°.

two orders of magnitude in difference between the highest and lowest fluxes. We also note that the escape flux of Segment 1 is lower compared to Segments 2–5. The error bars of Fig. 2c show relative standard deviations, obtained by multiplying the standard deviation from the average fluxes with the corresponding occurrence rate.

In order to estimate a total O^+ escape flux in the dayside magnetosheath, we have to define a typical area through which the observed fluxes flow. To a first approximation, one can assume a cylindrically symmetric flow, in which we let the average flux of a segment cross a corresponding annulus with a width similar to the segment width ($\sim 1\,R_E$). However, it is clear from Fig. 3 that most O^+ is observed at higher latitudes within a sector angle of 106°, in the YZ_{GSE}-plane. Hence, we consider the escape flux of each segment ($i = 1, 2, \ldots, 7$) to flow through a corresponding annulus sector with an area $A_i = 0.59\pi(r_{i+1}^2 - r_i^2)$, where we have chosen $r_i = (9+i)\,R_E$. The factor 0.59 ($= 106/180$) corresponds to escape fluxes mainly taking place at high latitudes (along open magnetic field lines) and not being significant far out on the flanks.

In Fig. 4 the calculated total flux segment by segment ($F_{tot,i} = F_i \cdot A_i$) is shown (red line/circles). The result yields the significance of the different segments to the overall total flux. Again Segment 2, 3 and 4 are dominant. Further outward the segment total flux decreases quickly. An estimate of the overall total flux is achieved by simply summing the segment total fluxes together. The blue line/circles in Fig. 4 illustrate the total flux, where circle i corresponds to the value $\sum_{k=1}^{i} F_{tot,k}$. Due to the small contributions from the most outward segments, the estimated total flux F_{tot} (blue line) approaches a constant value of $7 \times 10^{24}\,s^{-1}$.

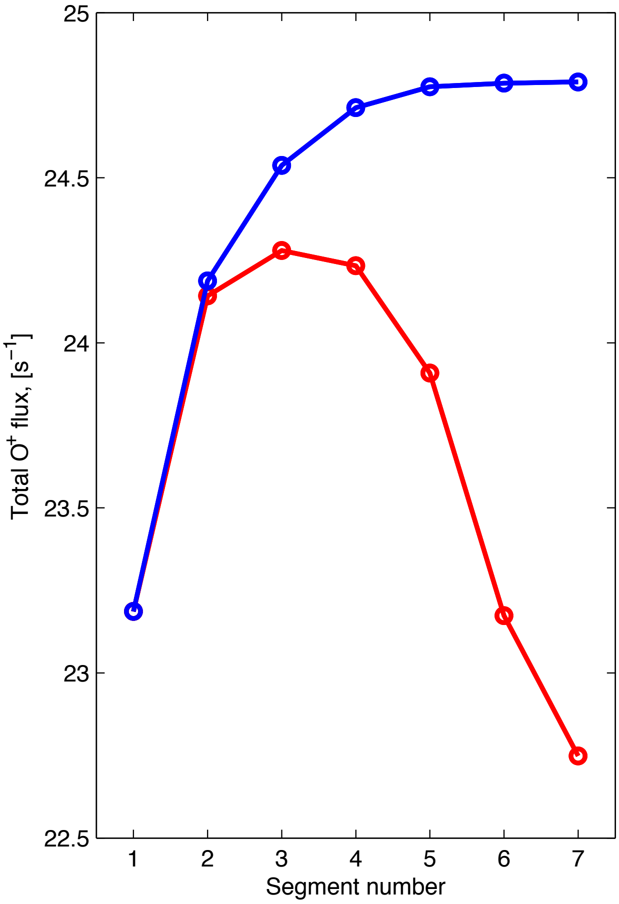

Fig. 4. Average escape flux for respective segment (red curve; see Fig. 1) and the total escape flux (blue curve). The total escape flux is calculated by summarizing the flux from respective segment in the sunward direction.

4 Discussion

The O^+ magnetosheath data set is described in Sect. 2.1. The lower limit of the ion energy (3 keV) does not exclude much real O^+ data, since O^+ ions have to be accelerated significantly in order to escape directly into the magnetosheath from the dayside mantle or the cusp (Slapak et al., 2012). The decrease in the average flux (Fig. 2a) is correlated to a corresponding decrease in number density. This property is consistent with broader cusp/mantle flux tubes when the magnetopause reaches further out into space compared to when the magnetosphere is more compressed. Figure 2b shows the occurrence rate. The reason for a low value in Segment 1 is because the magnetopause seldom is compressed beneath that region (i.e., Segment 1 is normally within the magnetosphere). The occurrence rate in Segment 5–7 is low mainly because O^+ rarely reaches that far, consistent with the fact that the O^+ predominantly flows tangentially to the magnetopause. In Sect. 3 we defined annuluses with a thickness of 1 R_E through which we assume the escape flux crosses.

We found it reasonable to multiply the annulus area with 0.59, since most of the magnetosheath O$^+$ escape at high latitudes (from cusp and mantle), as indicated in Fig. 3. With these choices we estimate the total flux in the dayside magnetosheath to be $7 \times 10^{24}\,\mathrm{s}^{-1}$.

Nilsson (2011) measured O$^+$ fluxes of the order $10^{25}\,\mathrm{s}^{-1}$ in the high altitude cusp and mantle. The ions reaching these regions were energized significantly (e.g., Waara et al., 2011; Slapak et al., 2011; Nilsson, 2011; Nilsson et al., 2012) and will typically have too high parallel velocities to convect to the tail plasma sheet (Haaland et al., 2012). Hence, presumably most of the O$^+$ in the high altitude cusp and mantle will eventually escape, either downstream passing the neutral point or directly through the magnetopause along open magnetic field lines. The main portion of the dayside magnetosheath O$^+$ reported in this study can be seen as a population distinct from the O$^+$ in the high altitude cusp and mantle investigated by Nilsson (2011). For instance, the average magnetospheric O$^+$ flight trajectories studied by Nilsson et al. (2012) do not necessarily lead to the dayside magnetosheath. Also, in the studies of Nilsson (2011) and Nilsson et al. (2012), all magnetosheath data were discarded due to contamination from strong proton fluxes. Given that we observe O$^+$ in the magnetosheath over a similar range of X_{GSE} positions as the observations made inside the magnetosphere, it seems feasible that the magnetosheath fluxes should be added to the fluxes inside magnetosphere. An even stronger argument is that the observed magnetosheath O$^+$ better agrees with the mid-altitude flows at the equatorward edge of the cusp reported by Bouhram et al. (2004), which have higher perpendicular temperatures and parallel velocities than typically observed by Nilsson et al. (2012).

Adding the total flux in the dayside magnetosheath (already escaped) and the total flux in the high altitude cusp/mantle (will eventually escape) gives an escape rate of $\sim 1,\ 7 \times 10^{25}$. Yau and André (1997) reported a cusp outflow at lower altitudes of $\sim 2 \times 10^{25}\,\mathrm{s}^{-1}$, which indicates that a majority of the outflowing O$^+$ ions directly escape along open field lines. Seki et al. (2001) estimated a total escape rate of $0,\ 5 \times 10^{25}\,\mathrm{s}^{-1}$, including leakage of dayside plasma sheet and ring current O$^+$ across the magnetopause through finite gyroradius effects, escape with so-called plasmoids and escape in the tail passing the neutral point. This result points to the direct escape into the interstellar space along open magnetic field lines being the dominant loss route for O$^+$ plasma in the terrestrial magnetosphere.

The position of the magnetopause depends on the solar wind conditions, and it is consequently highly variable. We observe O$^+$ in the magnetosheath up to several hours after the satellites cross the magnetopause, and it is therefore impossible to determine a measurement position relative to the magnetopause, simply because we do not know where the magnetopause is positioned at that specific moment. In this study we have not taken into consideration the position of the magnetopause, but stayed in a fixed reference frame (the GSE coordinate system), and therefore can not draw any explicit conclusions on the O$^+$ magnetosheath flux characteristics as a function of distance to the magnetopause. However, it is obvious from visual inspection that most O$^+$ observations in the magnetosheath are made immediately at or close to the magnetopause. Therefore, it may be possible to study the magnetosheath O$^+$ characteristics as a function of distance to the magnetopause after all, if considering only the close-to-magnetopause observations and using multi-spacecraft in situ measurements for determining the positions relative to the magnetopause. A study like that should be interesting to consider in the future, in order to get a more complete picture of the magnetosheath O$^+$ characteristics.

5 Conclusions

We have presented a statistical study on O$^+$ escape flux in the high-latitude dayside magnetosheath.The flow is predominantly tangentially to the magnetopause, and the majority of the O$^+$ is observed close to the magnetopause. Consequently, O$^+$ generally does not reach much further out into the magnetosheath at the dayside, but is quickly picked up by the solar wind and flows anti-sunward.

The total escape flux in the dayside magnetosheath is estimated to be $7 \times 10^{24}\,\mathrm{s}^{-1}$. Considering also the hot and fast O$^+$ observed in the high altitude cusp and mantle (which can be assumed to eventually escape), a significant part of the observed outflow/upflow of O+ in the cusp/polar cap presumably escape directly along open magnetic field lines from the high-latitude dayside magnetosphere or further downstream in the tail.

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References

Abe, T., Watanabe, S., Whalen, B., Yau, A. W., and Sagawa, E.: Observations of polar wind and thermal ion outflow by Akebono/SMS, J. Geomagn. Geoelectr., 48, 319–325, 1996.

André, M., Crew, G. B., Peterson, W. K., Persson, A. M., Pollock, C. J., and Engebretson, M. J.: Ion heating by broadband low-frequency waves in the cusp/cleft, J. Geophys. Res., 95, 20809–20823, 1997.

Bouhram, M., Klecker, B., Miyake, W., Rème, H., Sauvaud, J.-A., Malingre, M., Kistler, L., and Blăgău, A.: On the altitude dependence of transversely heated O$^+$ distributions in the cusp/cleft, Ann. Geophys., 22, 1787–1798, doi:10.5194/angeo-22-1787-2004, 2004.

Escoubet, C. P., Fehringer, M., and Goldstein, M.: Introduction The Cluster mission, Ann. Geophys., 19, 1197–1200, doi:10.5194/angeo-19-1197-2001, 2001.

Haaland, S., Eriksson, A. I., Engwall, E., Lybekk, B., Nilsson, H., Pedersen, A., Svenes, K., Förster, M., Li, K., Johnsen, C., and Østgaard, N.: Estimating the capture and loss of cold plasma from ionospheric outflow, J. Geophys. Res., 117, A07311, doi:10.1029/2012JA017679, 2012.

Hirahara, M., Terasawa, T., Mukai, T., Hoshino, M., Saito, Y., Machida, S., Yamamoto, T., and Kokubun, S.: Cold ion streams consisting of double proton populations and singly charged oxygen observed at the distant magnetopause by Geotail: A case study, J. Geophys. Res., 102, 2359–2372, 1997.

Horwitz, J. L.: The tail lobe ion spectrometer, J. Geophys. Res., 91, 5689–5699, doi:10.1029/JA091iA05p05689, 1986.

Kasahara, S., Hasegawa, H., Keika, K., Miyashita, Y., Nishino, M. N., Sotirelis, T., Saito, Y., and Mukai, T.: Escape of high-energy oxygen ions through magnetopause reconnection under northward IMF, Ann. Geophys., 26, 3955–3966, doi:10.5194/angeo-26-3955-2008, 2008.

Lennartsson, O. W., Collin, H. L., and Peterson, W. K.: Solar wind control of Earth's H^+ and O^+ outflow rates in the 15-eV to 33-keV energy range, J. Geophys. Res, 109, A12212, doi:10.1029/2004JA010690, 2004.

Liao, J., Kistler, L. M., Mouikis, C. G., Klecker, B., Dandouras, I., and Zhang, J.-C.: Statistical study of O$^+$ transport from the cusp to the lobes with Cluster CODIF data, J. Geophys. Res., 115, A00J15, doi:10.1029/2010JA015613, 2010.

Marcucci, M. F., Bavassano Cattaneo, M. B., Pallocchia, M., Amata, E., Bruno, R., Di Lellis, A. M., Formisano, V., Rème, H., Bosqued, J. M., Dandouras, I., Sauvoud, J. A., Kistler, L. M., Moebius, E., Klecker, B., Carlson, C. W., Parks, G. K., McCarthy, M., Korth, A., Lundin, R., and Balogh, A.: Energetic magnetospheric oxygen in the magnetosheath and its response to IMF orientation: Cluster observations, J. Geophys. Res., 109, A07203, doi:10.1029/2003JA010312, 2004.

Nilsson, H.: Heavy ion energization, transport, and loss in the Earth's magnetosphere, in: The Dynamic Magnetosphere, edited by: Liu, W. and Fujimoto, M., IAGA, Springer, 3, 315–327, doi:10.1007/978-94-007-0501-2_17, 2011.

Nilsson, H., Waara, M., Arvelius, S., Marghitu, O., Bouhram, M., Hobara, Y., Yamauchi, M., Lundin, R., Rème, H., Sauvaud, J.-A., Dandouras, I., Balogh, A., Kistler, L. M., Klecker, B., Carlson, C. W., Bavassano-Cattaneo, M. B., and Korth, A.: Characteristics of high altitude oxygen ion energization and outflow as observed by Cluster: a statistical study, Ann. Geophys., 24, 1099–1112, doi:10.5194/angeo-24-1099-2006, 2006.

Nilsson, H., Barghouthi, I. A., Slapak, R., Eriksson, A., and André, M.: Hot and cold ion outflow: spatial distribution of ion heating, J. Geophys. Res., 117, A11201, 2012.

Paschmann, G., Scopke, N., Haerendel, G., Papamastorakis, J., Bame, S. J., Asbridge, J. R., Gosling, J. T., Hones, E. W., and Tech, E. R.: ISEE plasma observations near the subsolar magnetopause, Space Sci. Rev., 22, 717–737, 1978.

Rème, H., Aoustin, C., Bosqued, J. M., Dandouras, I., Lavraud, B., Sauvaud, J. A., Barthe, A., Bouyssou, J., Camus, Th., Coeur-Joly, O., Cros, A., Cuvilo, J., Ducay, F., Garbarowitz, Y., Medale, J. L., Penou, E., Perrier, H., Romefort, D., Rouzaud, J., Vallat, C., Alcaydé, D., Jacquey, C., Mazelle, C., d'Uston, C., Möbius, E., Kistler, L. M., Crocker, K., Granoff, M., Mouikis, C., Popecki, M., Vosbury, M., Klecker, B., Hovestadt, D., Kucharek, H., Kuenneth, E., Paschmann, G., Scholer, M., Sckopke, N., Seidenschwang, E., Carlson, C. W., Curtis, D. W., Ingraham, C., Lin, R. P., McFadden, J. P., Parks, G. K., Phan, T., Formisano, V., Amata, E., Bavassano-Cattaneo, M. B., Baldetti, P., Bruno, R., Chionchio, G., Di Lellis, A., Marcucci, M. F., Pallocchia, G., Korth, A., Daly, P. W., Graeve, B., Rosenbauer, H., Vasyliunas, V., McCarthy, M., Wilber, M., Eliasson, L., Lundin, R., Olsen, S., Shelley, E. G., Fuselier, S., Ghielmetti, A. G., Lennartsson, W., Escoubet, C. P., Balsiger, H., Friedel, R., Cao, J.-B., Kovrazhkin, R. A., Papamastorakis, I., Pellat, R., Scudder, J., and Sonnerup, B.: First multispacecraft ion measurements in and near the Earth's magnetosphere with the identical Cluster ion spectrometry (CIS) experiment, Ann. Geophys., 19, 1303–1354, doi:10.5194/angeo-19-1303-2001, 2001.

Seki, K., Hirahara, M., Terasawa, T., Mukai, T., Saito, Y., Machida, S., Yamamoto, T., and Kokubun, S.: Statistical properties and possible supply mechanisms of tailward cold O$^+$ beams in the lobe/mantle regions, J. Geophys. Res., 103, 4477–4489, 1998.

Seki, K., Elphic, R. C., Hirahara, M., Terasawa, T., and Mukai, T.: On atmospheric loss of oxygen ions from Earth through magnetospheric processes, Science, 291, 1939–1941, 2001.

Shue, J.-H., Chao, J., Fu, H., Russell, C., Song, P., Khurana, K., and Singer, H.: A new functional form to study the solar wind control of the magnetopause size and shape, J. Geophys. Res., 102, 9497–9511, 1997.

Slapak, R., Nilsson, H., Waara, M., André, M., Stenberg, G., and Barghouthi, I. A.: O$^+$ heating associated with strong wave activity in the high altitude cusp and mantle, Ann. Geophys., 29, 931–944, doi:10.5194/angeo-29-931-2011, 2011.

Slapak, R., Nilsson, H., Westerberg, L. G., and Eriksson, A.: Observations of oxygen ions in the dayside magnetosheath associated with southward IMF, J. Geophys. Res., 117, A07218, doi:10.1029/2012JA017754, 2012.

Taktakishvili, A., Zimbardo, G., Amata, E., Savin, S., Greco, A., Veltri, P., and Lopez, R. E.: Ion escape from the high latitude magnetopause: analysis of oxygen and proton dynamics in the presence of magnetic turbulence, Ann. Geophys., 25, 1877–1885, doi:10.5194/angeo-25-1877-2007, 2007.

Waara, M., Slapak, R., Nilsson, H., Stenberg, G., André, M., and Barghouthi, I. A.: Statistical evidence for O+ energization and outflow caused by wave-particle interaction in the high altitude cusp and mantle, Ann. Geophys., 29, 945–954, doi:10.5194/angeo-29-945-2011, 2011.

Yau, A. W. and André, M.: Sources of ion outflow in the high latitude ionosphere, Space Sci. Rev., 80, 1–25, 1997.

Zong, Q.-G. and Wilken, B.: Layered structure of energetic oxygen ions in the dayside magnetosheath, Geophys. Res. Lett., 25, 4121–4124, 1998.

Zong, Q.-G., Wilken, B., Fu, S. Y., Fritz, T. A., Korth, A., Hasebe, N., Williams, D. J., and Pu, Z.-Y.: Ring current oxygen ions escaping into the magnetosheath, J. Geophys. Res., 106, 25541–25556, 2001.