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O^+ transport in the dayside magnetosheath and its dependence on the IMF direction

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Abstract. Recent studies have shown that the escape of oxygen ions (O^+) into the magnetosheath along open magnetic field lines from the terrestrial cusp and mantle is significant. We present a study of how O^+ transport in the dayside magnetosheath depends on the interplanetary magnetic field (IMF) direction. There are clear asymmetries in the O^+ flows for southward and northward IMF. The asymmetries can be understood in terms of the different magnetic topologies that arise due to differences in the location of the reconnection site, which depends on the IMF direction. During southward IMF, most of the observed magnetosheath O^+ is transported downstream. In contrast, for northward IMF we observe O^+ flowing both downstream and equatorward towards the opposite hemisphere. We observe evidence of dual-lobe reconnection occasionally taking place during strong northward IMF conditions, a mechanism that may trap O^+ and bring it back into the magnetosphere. Its effect on the overall escape is however small: we estimate the upper limit of trapped O^+ to be 5 %, a small number considering that ion flux calculations are rough estimates. The total O^+ escape flux is higher by about a factor of 2 during times of southward IMF, in agreement with earlier studies of O^+ cusp outflow.

Keywords. Magnetospheric physics (magnetosheath; solar-wind–magnetosphere interactions)

1 Introduction

The study of the fate of ion outflow is interesting for the atmospheric evolution of Earth, as it hints to what extent interactions between the solar wind and the magnetosphere affect the planetary atmosphere. The strongest coupling between the solar wind and the ionosphere takes place in the cusp regions, where direct solar-wind energy input allows for ion heating and acceleration along newly opened magnetic field lines. Wave–particle interaction has been shown to be effective in heating outflowing O^+, with subsequent acceleration due to the mirror force, to the high temperatures and bulk velocities observed in the high-altitude cusp and mantle (Waara et al., 2011; Slapak et al., 2011). O^+ has also been observed in the tail as cold beams (Seki et al., 1998; Liao et al., 2010), likely coming from the cusp and mantle region (Nilsson et al., 2012; Liao et al., 2012). Nilsson (2011) and Nilsson et al. (2013) showed that the O^+ bulk velocities in the high-altitude cusp and mantle in general are large enough to reach the distant tail and escape, and they estimated the escape flux to be about $10^{25}\,s^{-1}$. Observations of O^+ in the dayside magnetosheath have been reported many times; see, e.g. Zong et al. (2001), Marcucci et al. (2004), Kasahara et al. (2008) and Slapak et al. (2012). A statistical study of O^+ in the high-latitude dayside magnetosheath was made by Slapak et al. (2013), showing that O^+ is common, contributing $0.7 \times 10^{25}\,s^{-1}$ to the total O^+ escape flux. The total O^+ escape flux of the mantles and the dayside magnetosheath is similar to the total O^+ cusp outflow flux of $2 \times 10^{25}\,s^{-1}$, as reported by Yau and André (1997).

Studies of ion outflow in high-latitude magnetospheric regions as a function of the direction of the interplanetary magnetic field (IMF) have been presented by a number of authors. Data obtained by the Toroidal Imaging Mass-Angle Spectrograph (TIMAS) instrument onboard the Polar satellite used by Lennartsson et al. (2004) indicate that the O^+ outflow is typically 2.5–3 times higher during southward IMF than northward IMF. A reason for this could be that the polar cap

– and consequently the mapped cusp – is greatly affected by the IMF direction. Sotirelis et al. (1998) estimated the size of the polar cap boundary by studying precipitating particles in the auroral oval, and found that the cap is generally a few times bigger during southward IMF than during northward IMF. The size of the cusp will affect the total ion outflow, consistent with the observations of Lennartsson et al. (2004). Also, an increase in energy input through the cusps from the solar wind during southward IMF contributes to enhanced ion outflows. A correlation between transient upflows and flux transfer events have been observed both in situ (Nilsson et al., 2008) and with ground-based instruments (Moen et al., 2004).

The magnetic topology in the dayside magnetosheath and its coupling to the geomagnetic field is strongly affected by the IMF direction. One could therefore expect the magnetosheath O^+ flows to act correspondingly. During times of southward IMF, the magnetosheath field lines reconnect with closed geomagnetic field lines, allowing for magnetospheric cusp particles to directly escape along the open field lines while moving in the antisunward direction. For northward IMF, reconnection events taking place in the lobes are more favourable. Ions leaving the cusp following these newly reconnected field lines will have a parallel velocity component towards the equatorial plane. If an IMF line reconnects in the lobe of both hemispheres (dual-lobe reconnection), it will close and be brought into the magnetosphere, bringing solar-wind plasma into the magnetosphere. This process is illustrated and discussed by Song and Russell (1992). Indications and evidence of dual-lobe reconnection have been addressed by Pitout et al. (2012) discussing overlapping ion structures in the mid-altitude cusp during northward IMF. Other examples of evidences of dual-lobe reconnection are presented by, e.g. Imber et al. (2007) and Marcucci et al. (2008). Also, Imber et al. (2006) presented observations of dual-lobe reconnection and concluded that the IMF clock-angle $\theta = \tan^{-1}(B_y/B_z)$ needs to be within $\pm 10°$ (i.e. strongly northward IMF) in order for the mechanism to take place.

Slapak et al. (2013) made a statistical estimate of the total O^+ escape flux in the dayside magnetosheath, with the assumption that all observed O^+ would escape. A central question is whether this assumption is feasible or if O^+ trapping related to dual-lobe reconnection events is significant. If dual-lobe reconnection is relatively common we would expect to see indications of this in the statistical O^+ flows and be able to quantitatively determine its effect on the total O^+ escape flux. In this paper we present a statistical study of O^+ transport in the dayside magnetosheath and its dependence on the IMF direction.

2 The data set

The data used in this study cover January–May, 2001–2003, when the Cluster formation regularly passed through the high-latitude dayside magnetosheath of both hemispheres during high solar activity conditions. The data were obtained by instruments onboard spacecraft 1 (Rumba), one of the Cluster mission spacecraft (Escoubet et al., 2001). The ion properties are measured by the Composition Distribution Function spectrometer (CODIF), described by Rème et al. (2001). The instrument provides data in the range of 40 eV e^{-1}–38 keV e^{-1} using a time-of-flight technique, resolving the major ion species. O^+ energies < 3 keV were discarded when calculating the moments in order to avoid contamination from the strong magnetosheath H^+ fluxes. The O^+ energy range generally reaches the upper instrument limit of 38 keV, and therefore the calculated O^+ moments are not significantly affected by the discarded low-energy data. The data set was constructed by visually identifying time intervals of clear O^+ data in the magnetosheath from ion energy spectrograms, and consists of about 10^5 data points, corresponding to approximately 150 h. The spatial distribution of the data set is shown in Fig. 1 for cylindrical coordinates. A typical magnetopause (Shue et al., 1997) is also plotted for a better overview of the spatial scale. Most O^+ observations are relatively close to the magnetopause, and due to the non-stationary nature of the magnetopause the observations are spatially smeared out. The same ion data set was used and described in more detail by Slapak et al. (2013). In addition to the ion data, we use corresponding magnetosheath background magnetic field data with a satellite spin resolution of 4 s, obtained by the fluxgate magnetometer (FGM), described by Balogh et al. (2001). Throughout the study geocentric solar ecliptic (GSE) coordinates are used for all quantities.

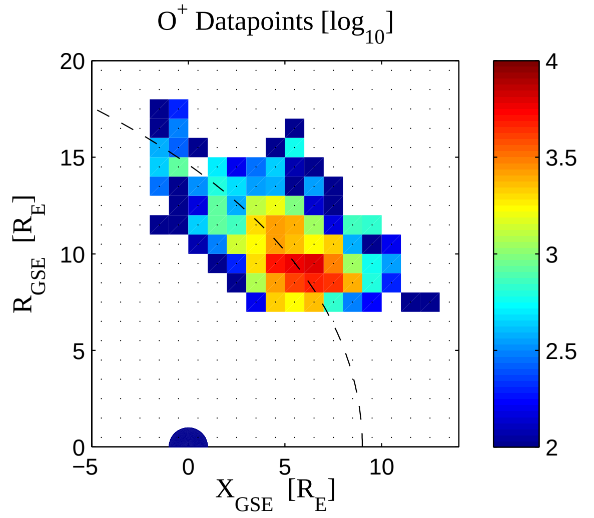

Figure 1. The spatial distribution of the magnetosheath O^+ data set, given in a cylindrical coordinate system with $R_{\mathrm{GSE}} = (Y^2_{\mathrm{GSE}} + Z^2_{\mathrm{GSE}})^{1/2}$. The colour bar corresponds to a logarithmic scale visualizing the number of data points in $1\,R_\mathrm{E} \times 1\,R_\mathrm{E}$ bins. Regions of no observations are left white.

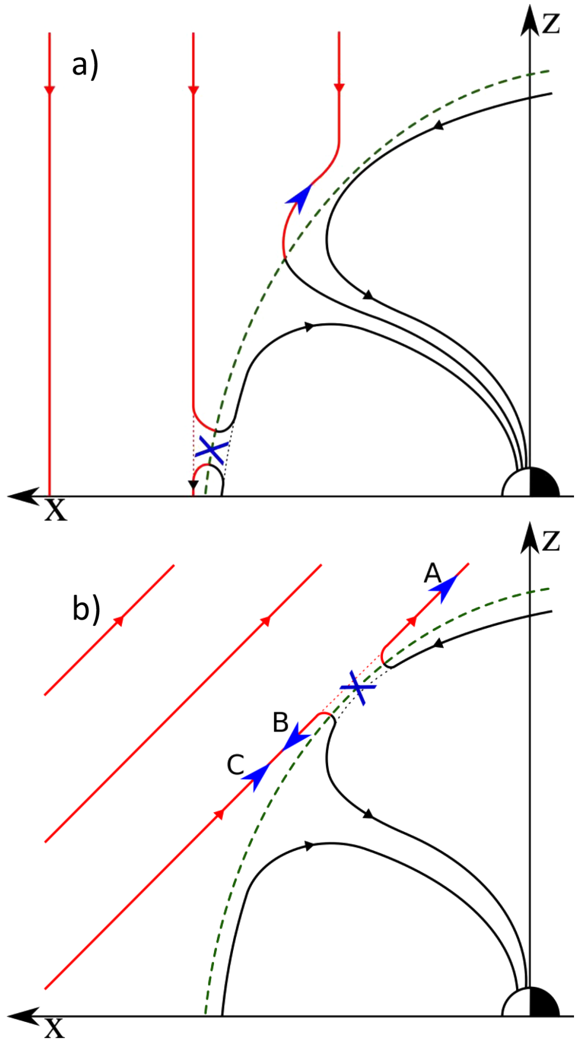

Figure 2. Illustrations showing typical reconnection events and corresponding magnetic topology for southward **(a)** and northward **(b)** respectively. The green dashed line corresponds to an approximate magnetopause, the red magnetic field lines correspond to IMF lines, the black corresponds to geomagnetic field lines, and the small arrows indicate field direction. The larger blue arrows correspond to different paths that ions entering the dayside magnetosheath may take.

3 Observations

The data set of magnetosheath O$^+$ described in Sect. 2 is divided into two subsets of northward and southward IMF, in order to study differences in the magnetosheath O$^+$ transport for the two different conditions. The probability of observing O$^+$ in the high-latitude dayside magnetosheath is higher for southward IMF than for northward IMF. The O$^+$ occurrence rate is defined as $N_{\mathrm{O}^+}/N_{\mathrm{total}}$, where N_{O^+} is the number of data points of observed O$^+$ in the magnetosheath for a given condition, and N_{total} is the total number of data points in the magnetosheath for the same condition. For southward and northward IMF, the O$^+$ occurrence rates are 22 and 14 % respectively.

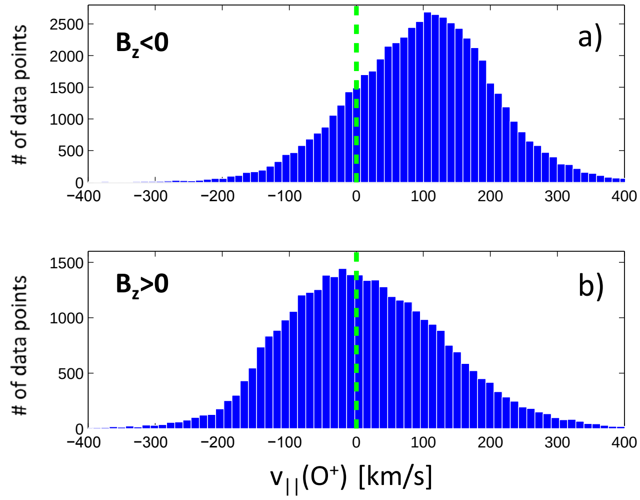

Figure 3. Histograms of the distribution of O$^+$ parallel bulk velocities for southward IMF **(a)** and northward IMF **(b)**.

When considering outflow along open field lines in the magnetosphere (e.g. in the cusps), the parallel velocity is commonly defined as positive in the direction away from Earth; i.e. parallel to the magnetic field direction in the Southern Hemisphere and antiparallel in the Northern Hemisphere. This way of defining the direction of the parallel velocity is suitable also when considering flows in the magnetosheath for southward IMF since a positive velocity then corresponds to escape flow (see Fig. 2a, illustrating the simple case of reconnection opening up geomagnetic field lines during southward IMF in the XZ plane). A histogram of the distribution of the observed parallel O$^+$ bulk velocities in the dayside magnetosheath is shown for southward IMF in the top panel of Fig. 3. About 82 % of the observed magnetosheath O$^+$ is seen as escape flow and 18 % as return flow.

For northward IMF we use the same definition for the sign of the parallel bulk velocity, and the parallel velocity distribution is presented in Fig. 3b. Around 55 % is positive, a considerably lower fraction than for southward IMF. Unfortunately this cannot be interpreted as simply as for southward IMF due to the difference in the magnetic topology. Figure 2b shows an example of reconnection taking place in the lobe for strongly northward IMF, and it is clear that positive parallel velocities correspond to equatorward flows. Ions leaving the cusp along the newly open field lines will have a velocity component along the field line towards the opposite hemisphere. Negative O$^+$ parallel bulk velocities correspond to flows along path A, corresponding to escape related directly to lobe reconnection events, or along path C, corresponding to flows originating from the opposite hemisphere. In order to differentiate between the different possible paths, we must also study and compare with the H$^+$ flow.

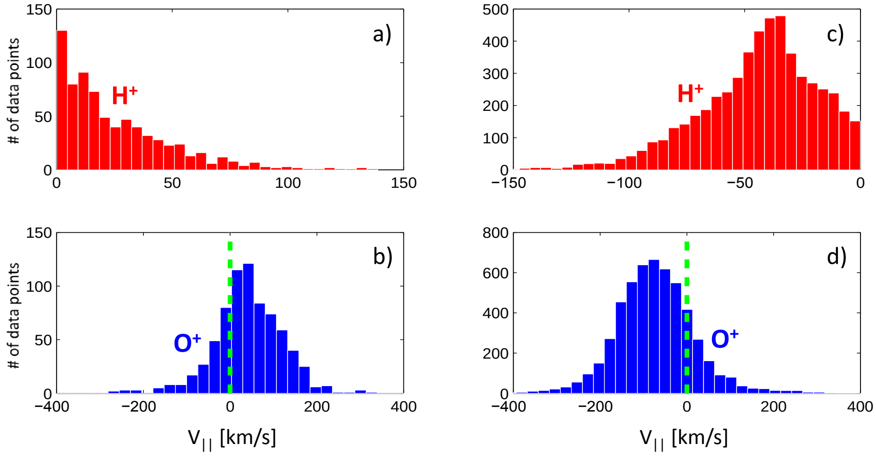

Figure 4. The occurrences of H$^+$ and O$^+$ parallel bulk velocities for northward IMF for small clock angles, $|\theta| < 30°$. Panels **(a)** and **(b)** show data when H$^+$ flows towards the equatorial plane, $v_\parallel(\mathrm{H}^+) > 0$, with H$^+$ and O$^+$ represented by red and blue bars respectively. Panels **(c)** and **(d)** show data for when H$^+$ flows away from the equatorial plane, $v_\parallel(\mathrm{H}^+) < 0$.

The magnetosheath flows around the magnetosphere, corresponding to either path A or C (negative parallel bulk flow). Therefore, we can assume that all observed positive H$^+$ parallel flows during small clock angles, $|\theta| = \tan^{-1}(|B_y|/B_z) < 30°$, take place along path B, on a magnetosheath field line that has reconnected in – at least – one of the lobes. Figure 4 shows histograms of the parallel bulk velocity occurrence for both H$^+$ and O$^+$, for data when $v_\parallel(\mathrm{H}^+)$ is positive (left plots) and when it is negative (right plots). 12 % of the observed H$^+$ during northward IMF and small clock angles is positive, and the absolute bulk velocities are typically considerably smaller than for the negative flow. The corresponding O$^+$ flows are mostly positive as well, flowing along the H$^+$ flows, but some (25 % of the corresponding data) is seen flowing in the opposite direction (along C). Most H$^+$ (88 %) is observed flowing in the negative direction, away from the equatorial plane, consistent with magnetosheath flow. The corresponding O$^+$ parallel velocities are also mostly negative, but some (18 %) are positive, going in the opposite direction as the H$^+$ flows. The interpretation of these numbers will be discussed in more detail in Sect. 4.

The distribution of parallel bulk velocities for H$^+$ and O$^+$ during times of large clock angles, $60° < |\theta| < 90°$, are shown in the two histograms in Fig. 5. For large clock angles the y component of the IMF is dominant and the situation is quite different from the situation illustrated in Fig. 2 since reconnection tends to take place out on the lobe flanks and because ions flowing out along the newly reconnected field lines will be restricted to the same hemisphere. The H$^+$ data show an equal amount of positive and negative parallel bulk velocities, whereas O$^+$ is mostly observed as positive (66 % of the large clock-angle data). The data set has not been divided into two subsets like for the small clock-angle data since it turns out this is not necessary in order to interpret the numbers.

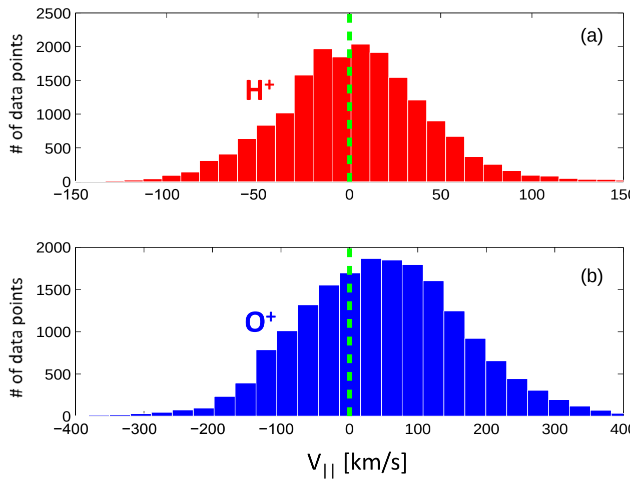

Figure 5. The occurrences of H$^+$ **(a)** and O$^+$ **(b)** parallel bulk velocities for northward IMF and large clock angles, $60° < |\theta| < 90°$.

4 Discussion

During southward IMF, the O$^+$ escape flow is dominant (82 %). Ions leaving the cusp travel along magnetic field lines leading downstream in the solar wind. The fraction seen as return flow may be O$^+$ that ended up in the magnetosheath due to finite gyroradius effects or O$^+$ originally on closed field lines being "pulled out" into the magnetosheath in the reconnection event.

As mentioned in Sect. 3, the O$^+$ flow during northward IMF is more complex and the statistics are more difficult to interpret. Figure 4 shows the ion data for small clock angles ($|\theta| < 30°$), and for $v_\parallel(\mathrm{H}^+) > 0$ and $v_\parallel(\mathrm{H}^+) < 0$. As argued in Sect. 3, in the case of small clock angles, positive H$^+$ parallel bulk velocities correspond to flows towards the equato-

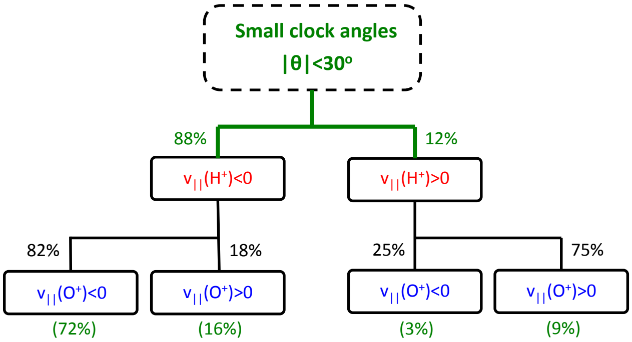

Figure 6. A tree diagram showing how the small clock-angle data are distributed in response to the parallel velocity directions for H^+ and O^+, where a positive parallel velocity corresponds to an equatorward flow.

rial plane (along path B in Fig. 2b). This H^+ flow (12 % of the small clock-angle data) is most likely to come from the cusp along newly reconnected field lines, going in the opposite direction as the magnetosheath flow, leading to smaller observed parallel bulk velocities. From the corresponding O^+ data in Fig. 4b it follows that O^+ – which also originates from the cusp – in general flows towards the equatorial plane as well. This O^+ flow (9 % of the total small clock-angle data) will reach the opposite hemisphere and either escape or be caught on a closed field line if lobe reconnection also occurs here before the ions pass the reconnection region. However, 25 % of the O^+ flows in the opposite direction to the H^+ and must consequently come from the opposite hemisphere. These data (corresponding to 3 % of small clock-angle data) strongly suggest dual-lobe reconnection due to evidence of reconnection taking place in both hemispheres.

Negative H^+ flows correspond to flow parallel to the magnetic field away from the equatorial plane, consistent with magnetosheath flow. Figure 4c shows that the absolute velocities are considerably faster than the positive H^+ flows. Most O^+ flows along with the H^+, but some (18 %) however flows opposite to the H^+. This positive O^+ flow must be along path B, which is consistent with the corresponding H^+ parallel velocity data which are low at the same time (not shown), indicating two H^+ populations going in opposite directions. This O^+ (16 % of the small clock-angle data) will either escape or be caught due to dual-lobe reconnection. That is, we see evidence of dual-lobe reconnection 3 % of the time, corresponding to small clock angles. Twenty-five percent of the time, we observe O^+ going towards the opposite hemisphere but we cannot determine whether it will escape or be caught. The rest (72 %) is seen as direct escape. A simpler overview of these numbers is given in the form of a tree diagram in Fig. 6.

Figure 5 shows the ion data for large clock angles, $60° < |\theta| < 90°$, with H^+ in the upper plot and O^+ in the lower plot. For large clock angles, the y component of the IMF is dominant and reconnection may take place equatorward of the cusps with closed geomagnetic field lines as well (Greenwald et al., 1995; Nilsson et al., 1997). In the aforementioned case, the scenario regarding ion escape is in principle the same as for escape during southward IMF. Therefore, if low-latitude reconnection is dominant in our data set, we would expect to see an O^+ parallel velocity distribution similar to the corresponding distribution for southward IMF (Fig. 3b). Clearly, this is not the case. In the case of the lobe reconnection during large clock-angle conditions, it tends to take place on the flanks, and this causes ions flowing out from the cusp to move towards the opposite quadrant in the same hemisphere, i.e. from $Y_{gse} > 0$ to $Y_{gse} < 0$, or vice versa. This flow will be observed as positive, using the same definition of the parallel bulk-velocity direction as before. Ions tailward of the reconnection region will on the other hand flow in the opposite direction, and will be observed as negative flow (along a path corresponding to A in Fig. 2b). That is, O^+ observed in the quadrant opposite to where reconnection took place will be measured as negative flow, and O^+ flow observed in the same quadrant as where reconnection took place will be measured as negative *or* positive, depending on where the spacecraft is positioned in relation to the reconnection point. Since the data are smoothly distributed over Y_{gse} between -15 and $+15\,R_E$ in both hemispheres (see Fig. 3 in Slapak et al., 2013), it would be more likely to observe positive O^+ flow than negative O^+ flow, which is also confirmed in Fig. 5b, where 66 % of the O^+ data are positive. The magnetosheath is diverted around the magnetosphere, and generally has a flow component in the positive y direction when $Y_{gse} > 0$ and in the negative y direction when $Y_{gse} < 0$. Again, due to the smooth distribution of the satellite position in Y_{gse} for both hemispheres, and since we observe $B_y > 0$ and $B_y < 0$ equally often, we expect to observe the H^+ to be negative and positive equally often. This is confirmed by the data presented in Fig. 5a, showing that 50 % of the H^+ data are negative, leaving the remaining 50 % positive. The data are therefore in good agreement with lobe reconnection dominating in our data set. This comes as no surprise as the observations take place at high latitudes (see Fig. 1), where we expect to see the effects of lobe reconnection more frequently. For large clock angles, there is no obvious mechanism able to bring O^+ back into the magnetosphere, and we can safely assume all O^+ under this conditions to be lost.

The data for intermediate clock angles, $30° < |\theta| < 60°$, are a mixture of the two different types of data corresponding to small and large clock angles, indicating that O^+ escape dominates here as well, even though a small part (smaller than for small clock angles) could be trapped. For large clock angles we argue that all observed O^+ could be considered lost. We can therefore expect that escape dominates during northward IMF, leading to a small total fraction of trapped O^+.

In order to confirm the small effect of O^+ trapping, we calculate an upper limit of the amount of trapped O^+, assuming all O^+ along path B in Fig. 2b to be trapped. This condition corresponds to 28% of the small clock-angle data. We also assume this number for the intermediate clock-angle data, but still assume all O^+ to escape for large clock angles, and get an upper limit of 5 % of the total O^+ (including southward IMF conditions). Therefore the estimate of the total O^+ escape presented by Slapak et al. (2013), assuming all observed O^+ to escape, is at most 5 % too big, which is a small maximum error considering that the estimate method in itself is rough, giving larger uncertainties.

The total O^+ escape flux during northward and southward IMF can be calculated in the same manner as Slapak et al. (2013) did for the total escape. This was done by binning the magnetosheath data and for each bin calculating the average flux ($cm^{-2}\,s^{-1}$) and the occurrence rate. Considering a cylindrically symmetric flow along the magnetopause in the polar regions, a cross-section area can be defined, allowing for estimation of the total escape flux (s^{-1}). The total escape flux during southward IMF ($\sim 4 \times 10^{24}\,s^{-1}$) is about a factor of 2 times larger than during northward IMF. Both the higher occurrence rate and observed average O^+ flux during southward IMF contribute to the higher total flux. The ratio between southward and northward O^+ total fluxes is comparable but somewhat smaller than the ratio of 2.5–3 obtained by Lennartsson et al. (2004) in the high-latitude magnetosphere.

5 Conclusions

O^+ transport and escape into the dayside magnetosheath and their dependence on IMF direction have been investigated. The total escape flux was found to be a factor of 2 larger for southward IMF than for northward IMF. The average flux as well as the occurrence rate for O^+ in the dayside magnetosheath are both higher during southward IMF, and both contribute to the higher total escape flux, a result consistent with studies showing higher cusp fluxes during southward IMF.

We present direct evidence of dual-lobe reconnection, observing ions of magnetospheric origin flowing in opposite directions in the dayside magnetosheath. When the clock angle is small we observe this 3 % of the time. This number may be somewhat bigger because we observe both (1) O^+ going towards the equatorial plane and (2) O^+ going away from the equatorial plane coming from the opposite hemisphere, without being able to determine whether it will escape or be trapped. However, dual-lobe reconnection is not likely to occur for larger clock angles, and consequently its impact on the total O^+ escape in the dayside magnetosheath is negligible. We can quantitatively determine that an upper limit of 5 % of magnetosheath O^+ is trapped in dual-lobe reconnection.

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