

Answer to the referee #1

We would like to thank the referee for his/her comments. We hereby answer the comments in green.

By going through the revisions, we found some errors in the automatic routine as well as the value of the perpendicular velocity in equation 1. The perpendicular velocity used in the submitted manuscript has been the bulk perpendicular velocity calculated from CODIF instrument. However, this perpendicular velocity is dominated by the ExB drift velocity, to what we added an additional initial ExB at the start of the tracing. Even though this was done, the velocity was underestimated compared to the thermal velocity of ions (for CODIF, the estimated thermal velocity is significantly higher than the bulk perpendicular velocity). We should have used the thermal velocity to begin with. We therefore reran all our events with the thermal velocity instead of the perpendicular velocity. We consequently updated all figures accordingly to the new simulations. The results are very similar but slightly different. Please also note that we removed “cusp” from the title to avoid confusion, since our observations are mainly in the plasma mantle region.

1. Implementation issues

The model is based on tracing test particles in a magnetosphere described by the T96 and Weimer 2001 models for magnetic field and potential, respectively. It is implied, but not directly stated, that the authors use the actual solar wind conditions for the events they study. Both T96 and Weimer 2001 are statistical models based on averages of observations under particular solar wind and IMF conditions. Some of the T96 input parameters take into account the history of relevant solar wind and IMF conditions. However, the Weimer models are known to have unphysically rapid responses to shocks and other interplanetary transients, as well as Alfvénic fluctuations in the IMF. Some caveats will be needed in cases where a shock or other interplanetary transient impacts the magnetosphere during the period covered in the modelling.

We use indeed the actual solar wind for the events studied. Most of strong disturbed conditions are removed from the data by Tsyganenko model requirements. Additionally, we looked at shocks through the Cfa interplanetary shocks database (<https://www.cfa.harvard.edu/shocks/>) simultaneously with the solar wind data. After a cross-check of these data, we removed 5 events. If a shock appeared in the next hours (after our events), we did not remove the event considering that if the solar wind conditions were too extreme at the initial time of our event, Tsyganenko requirements does not take the event into account. See clarifications in lines 132-133 of the revised manuscript.

The model is a test particle model which, as noted in the manuscript, neglects wave-particle interactions. This is a reasonable approximation in the outer magnetosphere but not in the inner magnetosphere, where some combination of chorus, EMIC, and ULF waves can produce pitch angle scattering and therefore affect loss rates (precipitating ions should not be considered losses in the context of this paper). Some caveats on this issue are also needed.

Our simulations are done mainly in the plasma mantle, which is considered to be in the outer magnetosphere (and very few events from the high-latitude cusp). In our automatized routine, we used a criteria of $R > 6 R_e$ in order to remove the inner magnetosphere. Therefore, we believe that our code is valid and gives reasonable trajectories for the ions observed in the

plasma mantle. Also, our main purpose is to confirm that majority of the O^+ in the plasma mantle are directly escaping into the solar wind or in the distant tail. Should our tracing lead the particles to the inner magnetosphere, we consider them as not lost, as discussed in the paper.

The simulation domain covers $60 \leq X \leq 10 \text{ Re}$. The justification for the upper limit is the magnetopause location. But $X = 10 \text{ Re}$ is merely the average location of the subsolar magnetopause; the actual location can move inward or outward depending on solar wind dynamic pressure. The simulation box should therefore be extended a bit sunward to cover the case of reduced solar wind pressure.

The simulation box is used for the electric field calculation along the magnetic field lines. Since we are tracing the ions from the plasma mantle and very few in the cusp, the limit of the electric field box is enough at $X = 10 \text{ Re}$. The Y and Z directions are more important from $X = 0 \text{ Re}$ to approximately $X = 5 \text{ Re}$, in order to include the moving magnetopause in the Y and Z directions. This aspect is covered by our limits in $|Y|$ and $|Z|$ directions that equals approximately 20 Re . The ions traced in the dayside plasma mantle are escaping almost directly through the magnetopause and never reach distances higher than the simulation box limit in the dayside. Therefore, the limit at 10 Re in X direction is enough for our study and extending the box would require more computational time without providing more accurate trajectories.

The authors treat the boundary of the inner magnetosphere as spherical and constant in time at a distance of 10 Re . The real boundary is neither static nor spherical: when solar wind dynamic pressure is elevated the nose of the magnetopause can be pushed inside 10 Re , which is its nominal location, and the relevant coordinate in the inner magnetosphere is the McIlwain parameter L rather than the radial distance R used in the manuscript.

We agree that the representation we used do not represent the real boundary. However, we only want a parameter that defines the boundary where the ions escape. In our case, we believe a spherical and static boundary for average conditions is good enough for statistics. For slightly disturbed conditions, the whole magnetosphere is compressed and our boundary is then overestimated and ions escape anyway. Please also note that strong disturbed conditions are removed by Tsyganenko model requirements.

2. Clarifications about the model

Equation (1) as written in the manuscript is not correct, because it has a scalar quantity on the left-hand side and a mixture of scalars and vectors on the right-hand side. If this was intended to be a vector equation, then all terms in the equation should be vectors. If the left-hand side was intended to be a scalar, then the right-hand side should be the square root of the sums of the squares of the components.

We are sorry for the confusion, equation (1) is a vector. We have corrected the equation in the new manuscript. Please note that we have updated the equation according to our new simulations (thermal velocity instead of bulk perpendicular velocity), lines 150-154. See also explanation at the beginning of the review.

Although the reader can deduce this from the subsequent figures, there should be an explicit statement in section 3.1 that the code traces the full 3-D velocity vector rather than using the guiding centre approximation.

We slightly changed the text, see lines 150-154. Additionally, equation (1) has been rewritten and therefore clarify the 3 dimensions of the velocity vector.

The authors do not give the X location for the listed magnetopause location of $|Y| = 13 R_E$ and $|Z| = 13 R_E$. The magnetopause can be approximated as cylindrical in the deep tail but still usually has some flaring at the $X = 0$ plane, which is where I think the quoted numbers are supposed to apply.

Yes, the numbers for Y and Z apply for $X=0$. We have added this detail in the new manuscript, see line 162.

In section 3.2, the authors should be explicit about using time-varying solar wind and IMF inputs.

We added a precision in the sentence saying that the solar wind conditions for each corresponding event are taken at the initial time (start time of the event). See lines 171-172 in the reviewed manuscript.

3. Miscellaneous issues

The result that the O^+ outflow increases by 1.5 orders of magnitude during active times compared to quiet times (specifically using Kp as an activity indicator) is not original with Slapak et al. (2017). The same result was obtained from DE data by Yau et al. (1985), JGR 90, 8417, doi:10.1029/JA090iA09p08417, which paper should be cited in that paragraph.

We have added this reference and Yau et al. (1988) as well, see lines 43-46. Slapak et al. study is actually based on their flux equations. The main difference between Slapak et al (2017) and Yau et al. (1985, 1988) is altitude. Slapak et al. examined the O^+ ions in the plasma mantle whereas Yau et al. examined lower altitudes (accordingly, the energy range is different) and this is why our simulations start from the plasma mantle rather than DE altitude that all past models used.

In the data selection thresholds given at line 119, I think the "and" should be an "or", since the intent is to exclude a velocity range in which the O^+ channel is contaminated by protons.

Yes, indeed the "and" should be changed in "or". We have corrected this in the new manuscript.

The quantity plotted on the X axis of Figure 4c is described as "minimum X distance" in the text, the figure caption, and the axis label. I do not think this is an accurate description of the quantity being plotted, since it covers the full range of the simulation box. A clearer description of this quantity would provide better insight into its physical significance.

We defined the minimum distance X_{min} as the minimum value in the X direction of the trajectory length. So in a trajectory of 280 steps, we take the minimum value in X direction within the 280 points. The maximum number of steps for a trajectory is 10000 and the shortest trajectory we obtained has 7 steps, the average trajectory steps is 1029. So, figure 4c represents the minimum value of each trajectory length, which indicates that most of the ions reach distances between $X = -10 R_E$ and $X = -20 R_E$. These ions might end their journey at that distance or may go back towards Earth after interacting with the plasma sheet. For most of the particles the minimum distance is their ending position. The peak at $X = -60 R_E$ includes the particles stopped at the limits of our model.

We have now clarify this "minimum X distance" in the new manuscript, see lines 224-227.

Answer to the referee #2

We would like to thank the referee for his/her comments. We hereby answer the comments in green.

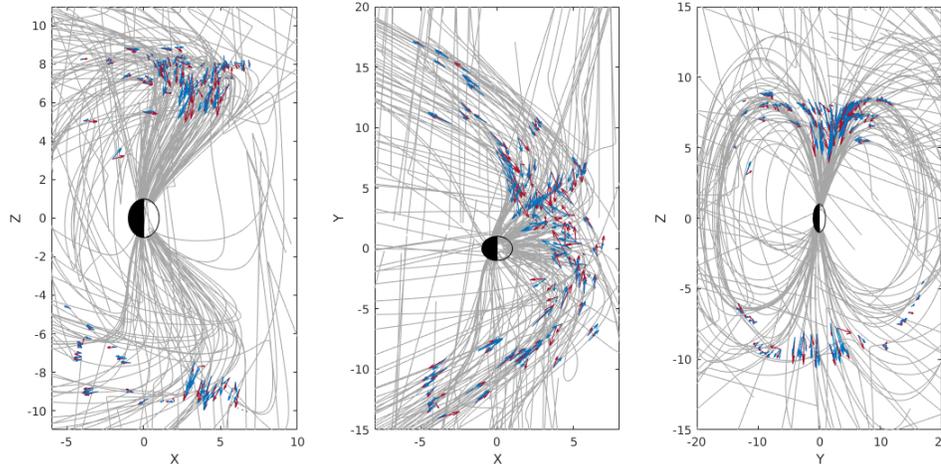
1) Line 170 - I don't understand the statement, "the perpendicular component of the velocity corresponds to the general variability of the data set". Are you saying that it is mainly statistical error represented here? It does seem that the thermal velocity would be more appropriate to use than the bulk perpendicular velocity, since it is mainly the pitch angle of the particle that is important for the trajectory, since the convection used is from the Weimer field. A distribution with a large pitch angle, could have net zero perpendicular velocity, but it would certainly lead to a higher parallel velocity along the trajectory, as you state in the next line. Can you explain better why you made the choice you did?

We originally used the bulk perpendicular velocity calculated with CODIF instrument, which is dominated by the ExB drift, which is included in the model and should not have been added to the particles. Just as the reviewer notes, we should have used the thermal velocity. We re-did the whole analysis with the thermal velocity instead. Since the thermal velocities were higher than our initial perpendicular velocity (1st manuscript), the total velocity was slightly underestimated. However, the final result did not change significantly.

See the general comment at the top of the answers and also equation (1) and paragraph 3.2 in the reviewed manuscript.

2) How good these trajectories are clearly depends on how good the field models used are. I suspect that the trajectories are quite sensitive to the initial conditions in the "start" location. The paper should include some discussion about how well the T96 model does in this region, and how sensitive the trajectories might be to discrepancies. The paper, Tsyganenko and Russell, 1999 implies that there needs to be additional corrections to correctly model the cusp. Has anything like this been included? Have the fields in the observation location been checked against the Tsyganenko fields, to make sure that they are in reasonable agreement? Has it been checked that the initial positions are in the "cusp" region of the Tsyganenko field?

The trajectories are indeed sensitive to the initial conditions. However, we checked the magnetic field provided by Cluster at the starting positions and the corresponding magnetic field calculated by Tsyganenko model. We found that both magnetic fields correspond pretty well to each other even though an increase in magnitude is observed closer to the Earth, see Fig. below (not shown in the manuscript). The blue and red components correspond to Cluster data and Tsyganenko respectively. We also checked the tracing of the lines individually for each event and we found that 4 events out of the 131 were most probably in the cusp (3%). Consequently, to avoid confusion for the reader, we removed "cusp" from the title and we focused our manuscript on the plasma mantle region.



3) For the example shown in Figure 3, 196 out of 200 are "long trajectories". However, in general, ion with "long trajectories" are only 11% of the sample, implying that the sample shown is not representative. Is this because of the chosen initial position? How much does the type of trajectory depend on the initial location? Perhaps a figure like Figure 5a (maybe blown up around the region of interest) that shows the average trajectory length in each bin would help clarify this? Or a set of 3 figures that show number of long trajectories, number of medium, and number of short in each bin? Or perhaps better would be figures that show the eventual fate of ions from different start locations (down tail, out dusk, into inner magnetosphere).

With our new events (131 instead of 136) the long trajectories are reduced to 5% of the sample. The starting points of the long trajectories do not influence how long the trajectory will be. We choose this particular example for the paper to illustrate the 3 types of trajectories even though long trajectories represent only 5% of the sample. To better illustrate the different trajectories we replace Figure 5 by a similar figure but divided in short, middle and long trajectories instead. We discuss this new figure lines 233 – 237 in the revised manuscript.

Line 209-215 - It is not clear what is meant by the statement "We define the escaping limit by the distance of the final position $R=10 R_e$." I suggest rewording to "An ion is defined to have "escaped the magnetosphere" if its final position is outside $R=10$."

We have added the sentence to clarify our definition of the escaping boundary, see lines 218-219.

Line 216 - Although this line is technically correct, I suggest rewording to make it clearer. "We determined the MAXIMUM distance in $|X|$ for each trajectory".

Since this parameter was not clear, we rewrote the sentences, see lines 224-227. See also comment #1.4 and #3.3 of referee #1. We defined the minimum X distance as the smallest value in the X direction for each ion trajectory. This parameter help to understand if ions move directly to the magnetopause or experience return flow (and interact with the plasma sheet) starting from the plasma mantle region. Therefore it is not the maximum distance $|X|$.

Lines 281 and 282, Magnetosphere misspelled twice.

Thank you, this has been corrected.

The fate of O^+ ions observed in the plasma mantle: particle tracing modelling and Cluster observations

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Abstract. Ion escape is of particular interest for studying the evolution of the atmosphere on geological time scales. Previously, using Cluster-CODIF data, we investigated the oxygen ion outflow from the plasma mantle for different solar wind conditions and geomagnetic activity. We found significant correlations between solar wind parameters, geomagnetic activity (Kp index) and the O^+ outflow. From these studies, we suggested that O^+ ions observed in the plasma mantle and cusp have enough energy and velocity to escape the magnetosphere and be lost into the solar wind or in the distant magnetotail. Thus, this study aims to investigate where do the ions observed in the plasma mantle end up. In order to answer this question, we numerically calculate the trajectories of O^+ ions using a tracing code to further test this assumption and determine the fate of the observed ions. Our code consists of a magnetic field model (Tsyganenko T96) and an ionospheric potential model (Weimer 2001) in which particles initiated in the plasma mantle region are launched and traced forward in time. We analysed **131** observations of plasma mantle events in Cluster data between 2001 and 2007, and for each event 200 O^+ particles were launched with an initial thermal and parallel bulk velocity corresponding to the velocities observed by Cluster. After the tracing, we found that 98% of the particles are lost into the solar wind or in the distant tail. Out of these 98%, 20% escape via the dayside magnetosphere.

1 Introduction

Before the 1970's, it was believed that the solar wind was the primary source of magnetospheric plasma. However, this conception became obsolete a few years later with the studies of Shelley et al. (1976); Sharp et al. (1977) who observed ionospheric O^+ ions with high velocities in the high-latitude ionosphere. A few decades later, it is now well known that ion upflow from the ionosphere is a significant source for the magnetosphere (Hoffman, 1968; Chappell et al., 1987; Abe et al., 1993) and it is accelerated through several processes to reach the high altitude cusp and plasma mantle. A part of this ion upflow is also known as the polar wind in analogy with the solar wind (Axford, 1968). The polar wind is composed of H^+ , He^+ , O^+ and electrons with an energy of a few eV and commonly observed between 1000 km and roughly 50 000 km. Polar wind observations have

been reviewed by Yau et al. (2007). At higher altitudes the terminology changes, and the term ionospheric outflow is used instead of polar wind, as it is complicated to distinguish solar wind H^+ from ionospheric H^+ . Furthermore, the ion outflow is then divided into two distinct populations, cold ions (up to a few tens of eV) and hot ions (up to a few tens of keV). The cold ions – detected with the spacecraft wake technique (Engwall et al., 2009) – are believed to be dominant for the magnetospheric plasma (André and Cully, 2012). These ions have been observed in the lobes (Haaland et al., 2009; Haaland et al., 2012; Liao et al., 2010) and have low enough parallel velocity so that convection dominates, and therefore will likely end up in the plasma sheet during strong solar wind conditions and southward interplanetary magnetic field (IMF) (Haaland et al., 2012). Under northward IMF the convection is more stable and weaker Haaland et al. (2012), meaning this cold population will escape in the distant tail and be lost into the solar wind. The energetic ions are frequently heated transversely to the magnetic field due to wave-particles interactions in the cusp (Norqvist et al., 1998; Strangeway et al., 2005; Slapak et al., 2011; Waara et al., 2011; Nilsson et al., 2012) and parallel to the magnetic field due to **magnetic mirror force, parallel electric field or centrifugal acceleration** (Nilsson et al., 2008; Nilsson, 2011). Arvelius et al. (2005) showed that O^+ ions are accelerated from less than 0.1 keV to more than 1 keV between 8 and 12 Re. The authors suggested that wave-particle interaction play the main role in the ion heating and subsequent acceleration. These energetic ions form the ion outflow at higher altitudes and several studies demonstrate the correlation between energetic ion outflow and solar and solar wind conditions (e.g., Peterson et al., 2001; Kistler et al., 2006; Li et al., 2012; Kistler and Mouikis, 2016; Schillings et al., 2019). It is the presence of a cusp and a polar cap that makes magnetised planets have atmospheric escape rates at least as high as planets without intrinsic magnetic fields (Gunell et al., 2018).

The main route of outflowing/escaping energetic ions is along open magnetic field lines, which include the polar cap, cusp and plasma mantle. The polar cap is defined as the footprint of the open magnetic field lines and the cusp as the entry of the solar wind into the magnetosphere. The plasma mantle is the region downstream of the cusp formed by reflected particles from the cusp, which are then convected toward the tail (Rosenbauer et al., 1975). **Using DE data at mid-altitude far below the plasma mantle, Yau et al. (1985, 1988) studied the dependency of the O^+ outflow in the polar cap on the geomagnetic activity (Kp) and the EUV flux (F10.7 index). At the solar maximum, they found about one order of magnitude increase for the O^+ and H^+ outflow between active ($3 \leq Kp \leq 5$) and quiet time ($Kp \leq 2$). Similarly at higher altitude, Slapak et al. (2017) studied the O^+ outflow in the plasma mantle and dayside high-latitude magnetosheath for different geomagnetic conditions using the Kp index. In these regions, the flux is high, indicating that a large part of outflowing ions at DE altitude reaches the Cluster altitude rather than entering the near-Earth plasma sheet.** They found that the O^+ escape rate increases by 1.5 orders of magnitude during very disturbed magnetospheric conditions ($Kp \geq 6$) compared to quiet conditions ($Kp \simeq 0-2$). Despite 5 years of data, Slapak et al. (2017) did not have enough statistics for extreme disturbances, and therefore Schillings et al. (2017, 2018) performed case studies of major geomagnetic storms ($Kp \geq 7+$) in order to complement the study of Slapak et al. (2017). The authors found a 2 orders of magnitude enhancement in the O^+ outflow for the major storms as compared to the average O^+ flux for the same year of each storm. They also suggested that the O^+ ions have been heated enough when they reach the plasma mantle to eventually escape the magnetosphere. During major geomagnetic storms Slapak and Nilsson (2018) estimated a perpendicular velocity of the plasma mantle O^+ to 35 km/s and a parallel velocity of 115 km/s, thus for

their particular example the ions would reach the plasma sheet around -50 Re. As the near-Earth X-line is pushed towards Earth during disturbed conditions, these ions are expected to escape in to distant tail.

Models and simulations have been extensively employed to investigate polar wind and ionospheric outflow. Schunk and Sojka (1989) simulated the polar wind behaviour using a combination of a low-altitude ionosphere-atmosphere and a high-altitude hydrodynamic model in a simulated region from 120 km to 9000 km. They discovered the complexity of the polar wind density structures in different altitude ranges as well as for geomagnetic variations. Polar wind behaviour during one idealised geomagnetic storm has been investigated by Schunk and Sojka (1997), who updated their model to an altitude coverage of 90 km to 9000 km for latitudes higher than 50° . They investigated the seasonal and solar cycle variations for four idealised geomagnetic storms (winter and summer solstices and solar minimum and maximum). They found that O^+ upflow increases over the polar cap during the storms, while O^+ is the dominant ion species at all polar latitudes. These results are similar to the ones by Barakat and Schunk (2006) who studied the generalised behaviour of the polar wind, also during an idealised geomagnetic storm using a macroscopic PIC (particle-in-cell) model. Their results agreed with satellite observations. At an intermediate lower altitude of 4000 km, Horwitz et al. (1994) determined the bulk velocity and temperature profiles of O^+ and H^+ in the polar wind using a semi-kinetic outflow model. They found that centrifugal forces increase the outflowing O^+ flux with 2 orders of magnitude when the convection electric field is enhanced from 0 mV/m to 100 mV/m. A similar result has been shown by Abudayyeh et al. (2015), who used a Monte Carlo simulation based on the Tsyganenko T96 model and included the effects of the ambipolar electric field as well as gravitational and mirror forces. Additionally, Abudayyeh et al. (2015) observed higher bulk velocities and densities (H^+ and O^+) in the cusp than in the polar cap.

At an altitude range of 1.2 Re to 15.2 Re, Barghouthi et al. (2016) employed the same 1-D Monte Carlo model used by Abudayyeh et al. (2015) to investigate energetic H^+ and O^+ outflows along two trajectories (from the polar cap to the cusp) and compared them with Cluster data. Considering the centrifugal acceleration, the ambipolar electric field and the wave-particle interaction, they concluded that the latter was the most important mechanism especially at higher altitudes (cusp). Finally, a statistical model of the fate of energetic ions showed that these ions are highly dependent on the magnetic field configuration. Therefore, for quiet magnetic field, more ions escape directly through the magnetopause, whereas for active magnetic field, the ions are convected towards the tail and reach the distant tail at 50 Re (Ebihara et al., 2006). Ebihara et al. (2006) also showed that under strong convection most of the ions in their model end up in the ring current.

Models about the polar wind and ion outflow behaviour already exist. These models take into account different altitudes and include the heating processes the ions are subject to. Ebihara et al. (2006) discussed the fates of the ions launched at different magnetic local time (MLT) and at 1 Re. Furthermore, Krcelic et al. (2019) estimated the fate of ions using the Tsyganenko T96 model and observations of ion velocities observed by Cluster satellites. They suggested that 69% of the ions escape the magnetosphere with 50% in the distant tail. Despite all those interesting studies, the fate of ions observed in the plasma mantle has not yet been well defined. This study aims to clarify if O^+ ion outflows observed in the plasma mantle will escape the magnetosphere and be lost into the solar wind as suggested previously from observations (Slapak et al., 2017; Slapak and Nilsson, 2018; Schillings et al., 2018). For a more accurate estimate of the fate of ions, the starting point should be high-altitude, so that much of the transverse heating and centrifugal acceleration are already included. In order to

answer this question, we traced particles in a combination of the Tsyganenko T96 (Tsyganenko, 1995) and the Weimer 2001 (Weimer, 2001) models. About 25 000 O^+ particles were launched from the plasma mantle with initial parameters taken from Cluster observations. This model thus incorporates the effect of the mirror force on the launched ions, centrifugal acceleration and $\mathbf{E} \times \mathbf{B}$ drift. It does not include any further wave particle interaction than what the ions had experienced prior to the observation point.

This paper is organised as follows: Section 2 describes the instrumentation and data set we used, followed by the method and a description of our code in Section 3. Section 4 and 5 present and discuss our results respectively. Finally, Section 6, summarises our study.

2 Instrument and data

2.1 Cluster and solar wind data

The Cluster mission (Escoubet et al., 2001) consists of four identical spacecraft flying in a tetrahedral formation with an apogee and perigee of approximately 19 Re and 4 Re respectively. On board the spacecraft, the Cluster Ion spectrometer (CIS) is composed of two instruments; the Hot Ion Analyser (HIA) and the COmposition and DIstribution Function analyser (CODIF) (Rème et al., 2001). The latter provides 3-D distributions of ions with an energy resolution of $\Delta E/E \sim 0.16$, an energy per charge range between 25 eV/q and 40 keV/q and a 360° field of view. The resolution of the data is usually 4 s, however, it can go up to 16 s. Those features enable observations of O^+ in different magnetospheric plasma regions. Additionally, Cluster has a FluxGate Magnetometer (FGM) (Balogh et al., 2001) with a mode sample frequency of 22.4 Hz. In our study, we use the magnetic field averaged over the spacecraft spin period (4 s).

The solar wind data were retrieved from the OMNIWeb database. This database consists of data from several satellites at diverse positions around Earth. In our simulations (see Section 3.2), we utilise the solar wind dynamic pressure and velocity, the IMF By and Bz components in high-resolution (5 min) as well as the magnetic Dst index (1 h).

2.2 Plasma mantle dataset

Our dataset consists of plasma mantle and **few** cusp events observed by the Cluster spacecraft 4 between 2001 and 2007. In order to only retrieve plasma mantle data, we apply several constraints on the observational data. Firstly, the CODIF O^+ counts are contaminated when strong proton fluxes from the magnetosheath are recorded at the same energy level as the O^+ ions (Nilsson et al., 2006). These false O^+ counts usually originate from the magnetosheath and lead to an underestimate of the O^+ velocity moment. The technique to remove these false counts is based on the $\mathbf{E} \times \mathbf{B}$ drift, because the drift is neither mass nor charge dependent. Consequently, using the kinetic energy equation, the cross talk signal is seen as an O^+ perpendicular bulk velocity that is 1/4 of the corresponding perpendicular proton velocity, and typically the O^+ density is higher than 2 cm^{-3} (for more details, we refer the reader to Nilsson et al. (2006)). We avoid these contaminated data (and therefore magnetosheath data) using the method described by Nilsson et al. (2006). However, we slightly changed the threshold defined by Nilsson et al.

(2006) because over the years the quality of the Cluster data devolved and so did the threshold. The new thresholds are given by $\frac{v_{tot}(O^+)}{v_{tot}(H^+)} < 0.2$ or $\frac{v_{tot}(O^+)}{v_{tot}(H^+)} > 0.5$ or $\frac{N_{O^+}}{N_{H^+}} > 0.25$.

To pick out only plasma mantle observations we implement different conditions for the high latitude regions. In these regions, the plasma beta β (O^+ and H^+) is typically higher than 0.05, whereas it is lower than 0.05 in the polar cap (Liao et al., 2010, 2015; Haaland et al., 2017). We use a threshold value of $\beta > 0.1$ for high latitude regions. Additionally, the perpendicular temperature of the protons should be lower than 1750 eV in order to distinguish plasma sheet from plasma mantle data (Nilsson et al., 2006; Kistler et al., 2006; Slapak et al., 2017). As partly mentioned above, the O^+ and H^+ densities are restricted to $n(H^+) > 10^{-3} \text{ cm}^{-3}$ and $10^{-3} \text{ cm}^{-3} < n(O^+) < 2 \text{ cm}^{-3}$ to keep only reliable velocity estimates. In order to study the fate of ions, we take O^+ data with an outward flow ($v_{\parallel} > 0$ or $v_{\parallel} < 0$ in the southern and northern hemispheres respectively). Finally, we use a spatial coverage restriction to remove the inner magnetosphere, which is defined by $-5 \text{ Re} < X_{\text{GSM}} < 8 \text{ Re}$ and $R_{\text{GSM}} = \sqrt{Y_{\text{GSM}}^2 + Z_{\text{GSM}}^2} > 6 \text{ Re}$ (see also Slapak et al. (2017)). Major geomagnetic storms data are removed to exclude other magnetospheric regions than the plasma mantle (Schillings et al., 2017). **Finally, we also excluded events associated with potential shock arrivals at Earth to avoid strong perturbations in the magnetosphere.**

When all the above conditions are met, we define one event by 60 data points or more in a row. Between 2001 and 2007, our automatic routine detected **131** events that met the region criteria and the model restrictions (see Section 3.1).

3 Methodology

The section aims at briefly describing how our model works and its inputs and outputs.

3.1 Particle tracing simulations

We use a test particle simulation code (Gunell et al., 2019) to compute ion trajectories in the magnetic fields given by the Tsyganenko T96 model (Tsyganenko, 1995) and electric fields derived from the ionospheric potential given by the Weimer 2001 model (Weimer, 2001). The electric field is defined on a grid, and during the test particle trajectory calculation the electric field at the particle position is found by interpolation. Before the trajectory calculation starts, we define the electrostatic potential V on a three-dimensional grid with a cell size of $1200 \text{ km} \times 1200 \text{ km} \times 1200 \text{ km}$ in the region $-60 < X < 10 \text{ Re}$, $|Y| < 19 \text{ Re}$ and $|Z| < 19 \text{ Re}$ by tracing the magnetic field lines from each cell down to the ionosphere, where we retrieve the potential from the Weimer model. The electric field is then found from the relationship $\mathbf{E} = -\nabla V$.

Figure 1 illustrates the magnetic field lines in light grey and the electric field grid in brown. This illustration represents the magnetosphere based on T96 and the grid for the interpolation of the electric field. Due to the limits of the Tsyganenko model, the electric field grid goes to -60 Re in the tail and 10 Re in the dayside (Tsyganenko, 1995). In the north-south, Z , and dawn-dusk, Y , directions, the limit of the grid are at $\pm 19 \text{ Re}$. Note that the illustration is not to scale.

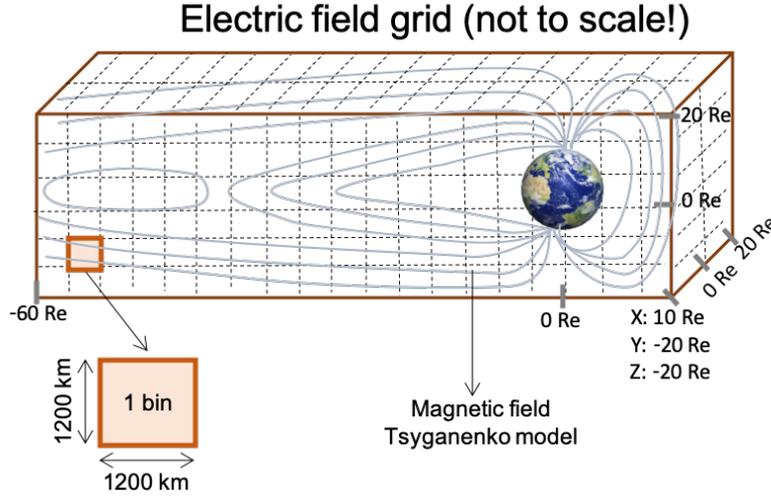


Figure 1. Schematic representation of the modelling of the Earth's environment. The Earth magnetosphere is represented in light grey and the brown grid displays the electric field grid. Note that the illustration is not to scale.

To launch a particle, its initial ion **3-D** velocity is calculated using the following equation

$$\begin{aligned}
 v_{tot} &= v_0 + v_{th} \\
 v_{tot} &= v_{\parallel} \frac{\mathbf{B}}{B} + v_{E \times B} + v_{th} \frac{\mathbf{E}}{E},
 \end{aligned} \tag{1}$$

where v_0 is the bulk velocity defined by v_{\parallel} and $v_{E \times B}$, the parallel and drift velocities respectively, v_{th} is the thermal velocity of the O^+ ion (see Section 3.2 for more details), B the magnetic field and E the electric field. Then, the electric field at the position of the O^+ ion is formed by interpolation of the field saved on the grid. Finally, from the interpolated electric field, a new velocity is calculated with the Boris algorithm (e.g. Birdsall and Langdon, 1991).

The last step is repeated as far as the limitations of the code allows it. The tracing uses a time step based on the gyro-period, so that our time step is $dt = 2\pi/20\omega_c$ whereas the maximum number of iterations is limited to 10000. In 99,93% of the cases, the particle stops because they reach the limit of our model (electric field grid), whereas for the 0.07% remaining the maximum number of the iterations have been completed.

The grid that defined the limit of our model is sufficient for our study because it includes the whole magnetosphere around Earth (magnetopause is defined around $X = 10 \text{ Re}$ in the dayside and about $|Y| = 13 \text{ Re}$ and $|Z| = 13 \text{ Re}$ for $\mathbf{X} = \mathbf{0} \text{ Re}$). **Note that small regions near the subsolar magnetopause are not included, however, they are not relevant for our study.** Further in the magnetotail, the magnetopause expands into a "cone shape" in the Y and Z direction and beyond 200 Re in the X direction. Our grid stops at $X = -60 \text{ Re}$ in the tail due to Tsyganenko model limits, moreover most of the particles reaching that distance will most likely be lost (see Sections 4 and 5 for more details). Concerning constraints, the Weimer model imposes no constraints on solar wind parameters, while Tsyganenko T96 does. Therefore, when an observation meet

the criteria described above it also has to match with Tsyganenko T96 constraints, which concerns the Dst index ($-100 \text{ nT} < \text{Dst} < 20 \text{ nT}$), the dynamic pressure ($0.5 \text{ nPa} < P_{\text{dyn}} < 10 \text{ nPa}$) and IMF B_z and B_y ($-10 \text{ nT} < B_z, B_y < 10 \text{ nT}$).

170 3.2 Inputs and outputs of the model

The inputs of the models are (a) solar wind parameters as required by the Tsyganenko- and Weimer models, (b) the positions, **the thermal and bulk parallel velocities, v_{\parallel} and v_{th} respectively**, based on Cluster observations. The solar wind parameters (see Section 2.1) are taken **at the initial time of** each corresponding event. The **131** plasma mantle events are automatically detected by a routine scanning Cluster data (see Section 2.2). During these events, we calculate the **thermal and bulk parallel** 175 velocities and retrieve the spacecraft positions. These parameters are then used to create the initial positions, v_{\parallel} and v_{th} of 200 O^+ ions (per event) that we trace forward in time.

Figure 2 shows the bulk parallel- and **thermal** velocities from Cluster data from a sample event in the northern hemisphere. This plasma mantle event occurred on 11th of June 2001 between 01:24 UT and 01:29 UT. The solid black line shows the weighted mean defined by $\sum v_{\parallel,i} n_i / \sum n_i$ (where i denote the observations, typically one 4 s measurement for CODIF), 180 whereas the dashed red lines display the standard deviations. For this event, the mean $v_{\parallel}(\text{O}^+)$ is $-109.01 \pm 44.54 \text{ km/s}$ and **the $v_{\text{th}}(\text{O}^+)$ is $120.22 \pm 35.3 \text{ km/s}$** . A uniform standard distribution of random values in these intervals $v_{\parallel} = [-64.47; -153.55] \text{ km/s}$ and $v_{\text{th}} = [84.92; 155.52] \text{ km/s}$ **give the initial v_{\parallel} and v_{th}** utilised as inputs for the forward traced particles. In a similar way, the initial positions of the 200 traced O^+ particles are randomly chosen in the interval $x = [2.046; 2.061]$, $y = [-8.643; -8.558]$, $z = [8.885; 8.886]$, which are the minimum and maximum positions of Cluster during the event (11.06.2001 - 185 approximately 5 min).

The output of the model give us the final positions of O^+ in the magnetosphere as well as the travelling times of the particles in the magnetosphere.

4 Observations and Results

We analysed **131** event based on Cluster observations between 2001 and 2007. For each event, we launched 200 O^+ ions 190 with various perpendicular and parallel velocities. Therefore, the statistics presented in this section are based on **26200** O^+ ions starting in the high altitude regions. Their ending positions are spread within the magnetosphere but a significant amount end up at the limit of our model. Figure 3 shows an example of 40 O^+ trajectories (out of the 200 computed) **spread in the magnetosphere**. This event occurred on 06.11.2001 during approximately 5 minutes (01:24 UT - 01:29 UT), the Dst index was -10 nT with a slightly southward IMF ($B_z = -0.486 \text{ nT}$) and negative B_y (-1.16 nT). The solar wind velocity was around 195 550 km/s and the dynamic pressure 1.74 nPa . The top panel in Fig. 3 displays the trajectories in the XZ plane, while the middle and bottom panels display the YZ and XY planes respectively. The different colours represent various trajectories, the crosses show the initial positions (noted by starting positions), whereas the asterisks show the final positions. This event clearly shows that ions from similar positions but with different velocities (see Fig. 2 for velocity range) can have very distinct trajectories. Part of the O^+ ions follow the magnetic field lines and stop at -60 Re in the distant tail (limit of the model), others

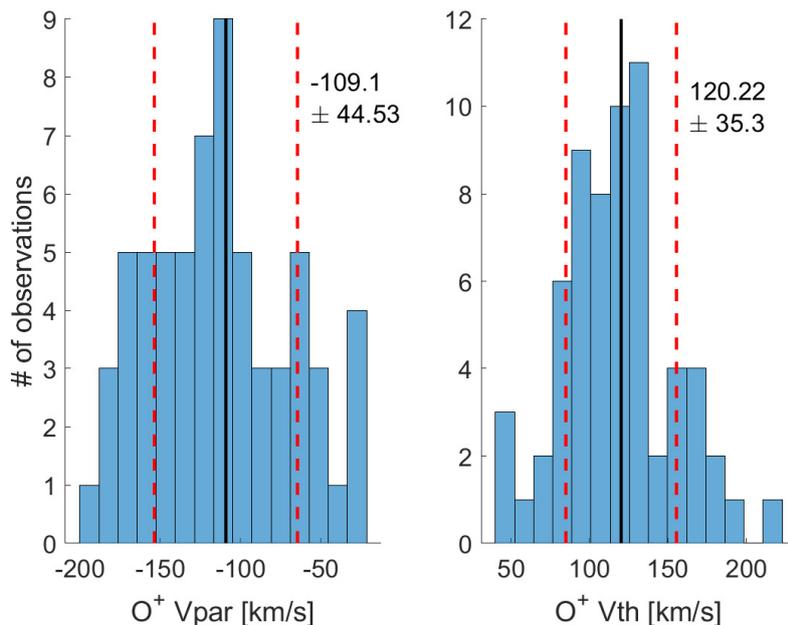


Figure 2. Cluster SC4 observations: Parallel and perpendicular components of the O⁺ velocity on 11.06.2001 between 01:24 UT and 01:29 UT. The solid black line represents the mean and the dashed red lines show the standard deviations.

200 are mirroring a few times before being lost on the flank (see bottom panel). Finally, a few ions are mirroring back and forth around Earth and end up in the cusp, the polar cap or simply in the plasma sheet. In this event (Fig. 3), **191** trajectories out of the 200 computed are considered to be long (more than 2000 iteration steps, see next paragraph for more details). In other events, we observed ions following magnetic field lines into the distant tail that eventually reach the plasma sheet around $X = -50$ Re and turn back toward Earth (not shown). Those particles are return flow (earthward flow), and we discuss their fate in
 205 the Discussion (see Section 5).

Figure 3 provides a good example of how different the trajectories could be spread starting from a similar position, however this particular example is not representative of our sample events. Since the plasma mantle is close to the magnetopause, some events (17%) have very short trajectories (approximately 5 min). Indeed, the O⁺ ions that are launched at high altitudes in the plasma mantle typically follow the magnetic field lines and reach the magnetopause almost immediately.
 210 Those ions escape into the magnetosheath and will most likely never turn back to the magnetosphere. Fig. 4a shows the length of the **26200** trajectories in our sample, the mean trajectory is about **767 iteration steps (or $10^{2.65}$ in the panel)**. We analysed the fate of the ions with short (**lower than 200 steps, average time 5 min**), middle (**200 to 2000 steps, average time 20 min**) and long (**over 2000 steps, average time 104 min**) trajectories and found that O⁺ trajectories with less than 2000 steps (short and middle) escape mainly from the flank of the magnetosphere and represents **95%** of our samples. Ions with longer
 215 trajectories represent **5%** of the total sample. Within the ions with a long trajectory, **35.5%** end up in the near-Earth plasma

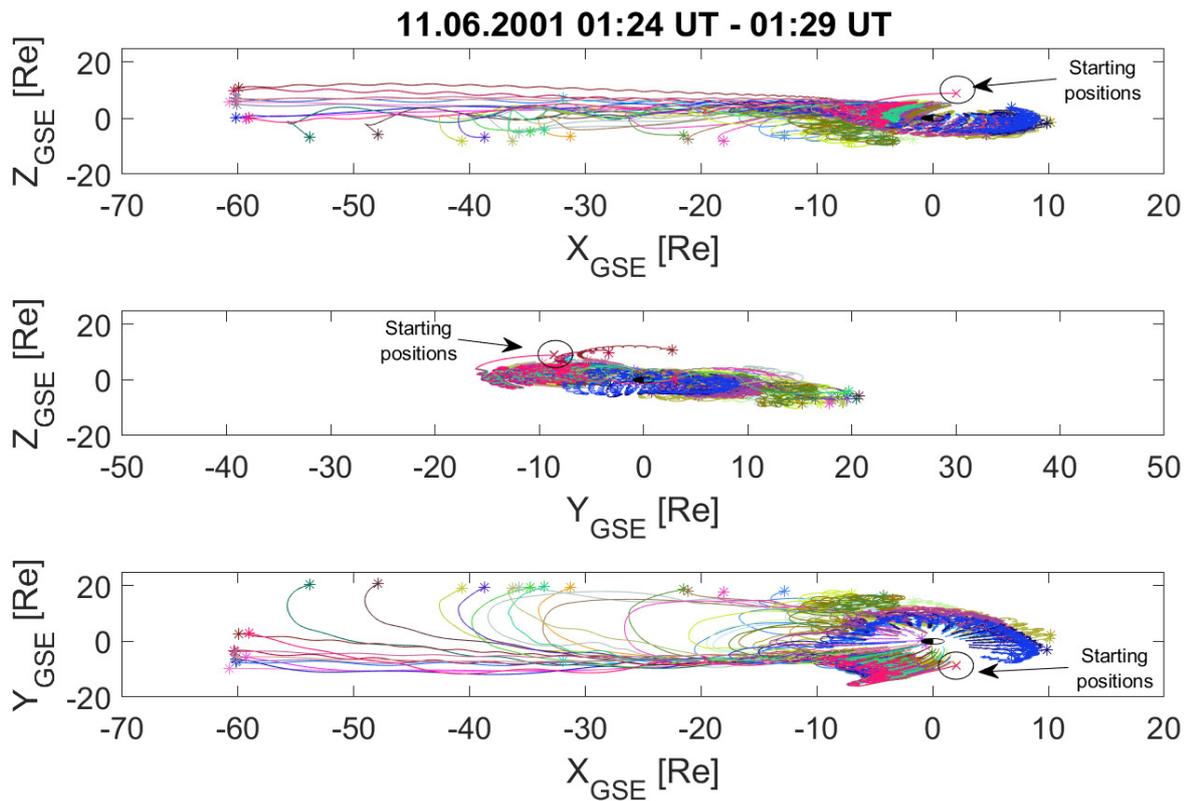


Figure 3. Example of 40 O^+ varied trajectories (different colours) from the plasma mantle on 11.06.2011 between 01:24 UT - 01:29 UT. The crosses denote the starting positions, whereas the asterisks denote the ending positions in the magnetosphere.

sheet (at geocentric distance lower than 10 Re). We defined the escaping limit by the geocentric distance of the final positions $R = \sqrt{X_{\text{fin}}^2 + Y_{\text{fin}}^2 + Z_{\text{fin}}^2}$ that equals 10 Re. **Thus, an ion is defined to have escaped the magnetosphere if its final position is outside 10 Re.** This is justified by the fact that if the tracing does not end due to the limits of iterations, such ions have left the simulation domain (except for 0.07% of the trajectories, see Section 3.1). Note that the minimum geocentric distance where the O^+ ions are launched is 7.64 Re (not shown). Only **2 %** of the total trajectories have their final positions below this limit (10 Re), hence **98 %** of the ions are escaping the magnetosphere. The geocentric distance R of the 26200 final positions is represented in the middle panel (b) of Fig. 4. The O^+ average final position is $R = 22.9$ Re.

Furthermore, in **Fig. 4c**, we determined the minimum distance in the X direction for each trajectory as the minimum value found in the X direction of each ion trajectory (given in Re). As an example, for a trajectory of 2000 steps, the minimum X distance is the minimum value (in the X direction) within the 2000 steps, which is not necessarily the final position of the ion. In **Fig. 4c**, each data point represents the minimum X distance of one trajectory. The average

minimum X distance is around -10 Re, which corresponds to the plasma mantle region if $|Z| > 5$ Re (see also on Fig. 5). This parameter is important because some particles that interact with the plasma sheet in the distant tail might come back close to Earth. However, such cases are rare because for a total of **849** trajectories having a X minimum distance beyond -50 Re only **23** trajectories finish their route close to Earth ($R < 10$ Re). The **826 remaining** are roughly equally spread between 10 Re and 64 Re.

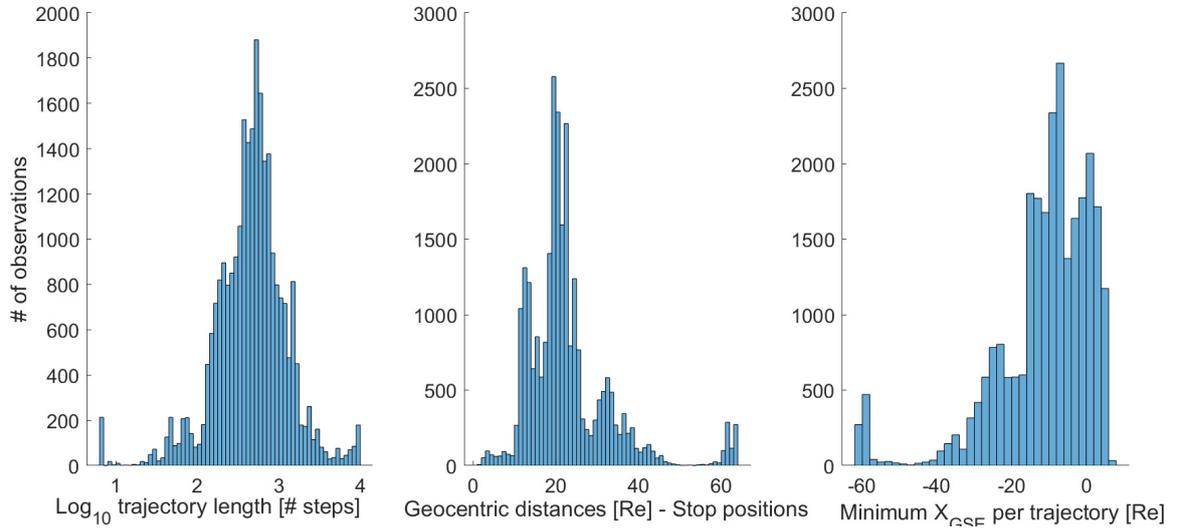


Figure 4. (a) Length of the 26200 O^+ trajectories in our sample. Note the logarithmic scale. (b) Final positions expressed in the geocentric distance R given in Re (see text for definition). (c) Minimum X distance for each trajectory.

Fig. 5 shows the start (upper panels) and stop (lower panels) positions of the O^+ trajectories in cylindrical coordinates ($R_{cyl} = \sqrt{Y^2 + Z^2}$). The columns gives the length of the trajectories; short, middle and long as defined above. The colour bar represents the numbers of trajectories per bin (1 Re x 1 Re) and the red dashed line represents the average magnetopause for the corresponding events. In the first line, we clearly see that particles are launched in the plasma mantle region, while on the second one, the ending positions are spread at high R_{cyl} . O^+ ions from the plasma mantle do not necessarily escape in the distant tail as we suggested in Slapak et al. (2017); Schillings et al. (2019), but they are escaping almost directly through the magnetopause because of their high velocities in these regions. The magnetopause is identified by abrupt changes in the tracing of the magnetic field lines, once the magnetopause is crossed, the field lines become straight and follow the IMF direction. Similarly, we observe **22%** of the ions are escaping in the dayside ($X > 0$ Re). Note that the vertical line of ions at -60 Re have been stopped tracing due to the limit of our code.

The associated scaled O^+ flux (defined as the net outward flux mapped to an ionospheric reference altitude of 1000 km with a magnetic strength of 50 000 nT) is about $10^{13} \text{ m}^{-2}\text{s}^{-1}$ in average (not shown). The highest O^+ scaled flux, $10^{14} \text{ m}^{-2}\text{s}^{-1}$, is observed around Earth ($-3 \text{ Re} < X < 3 \text{ Re}$) at $R_{cyl} = 23 \text{ Re}$. In contrast, the lower scaled flux is observed below $R_{cyl} = 10$ Re and between $15 \text{ Re} < R_{cyl} < 20 \text{ Re}$ for X lower than -20 Re.

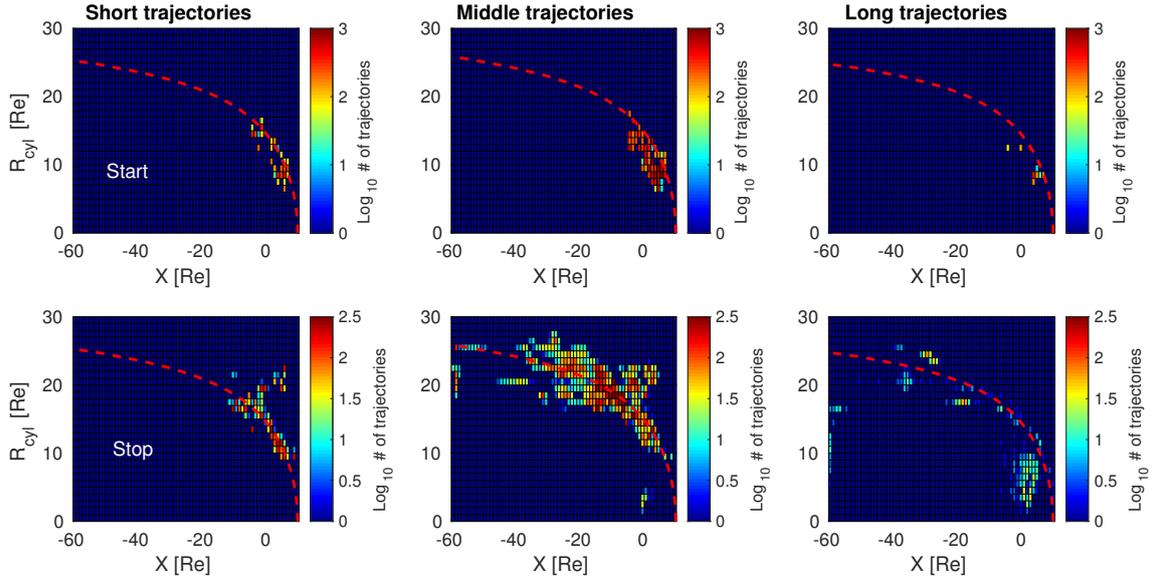


Figure 5. Cylindrical coordinates of the starting and ending positions of the launched O^+ ions **depending on the length of their trajectory** (see definitions in the text). The upper panels show the starting positions, while the lower panels show the ending positions. The colour bar represents the number of trajectories in each bin. The red dashed line shows to the average magnetopause for the corresponding events.

5 Discussion

In our 131 events based on Cluster-CODIF observations, the parallel and **thermal** components of the velocities during the events are taken as inputs to our forward tracing model (see Section 3.2 and Fig. 2). From these observations, we found that O^+ ions observed in the plasma mantle have a parallel velocity **being comparable to, or lower than the thermal velocity** as expected. More precisely, the ratio between the velocity components ($|v_{\parallel}|/v_{th}$) is 0.65 ± 0.44 . Since the bulk perpendicular velocity is much smaller than the parallel bulk velocity in the plasma mantle (Vaith et al., 2004), the O^+ ions in the mantle can be characterised by the parallel bulk velocity and the thermal velocity. The bulk perpendicular velocity is relatively small, but would be important for their trajectories, in particular, storm time, and/or southward IMF (Haaland et al., 2008). Indeed, in the 13% of our events with higher convection velocity, more than half have a corresponding Dst index below -20 nT and a southward IMF.

We do not find any strong correlation between geomagnetic activity (Dst) and the final positions. For the IMF direction, we identify 48% of the events are associated with northward IMF and the final positions of these ions to be mainly spread between $R_{geoc} = 10$ Re and $R_{geoc} = 40$ Re (95% of the events with northward IMF). A similar trend is observed for the remaining 52% events associated with southward IMF. Thus, the direction of the IMF do not influence in which magnetospheric region the ions end up. However, if we consider only the ions with their ending positions in $R_{geoc} < 10$ Re, they occur **during southward IMF**

(67%). This result can be compared to the cold ion outflow observed in the lobes during southward IMF. Haaland et al. (2012) found that for southward IMF the cold ion outflow is convected toward the plasma sheet due to strong convection, whereas for IMF directed northward convection is stagnant, so that cold ion outflow reach the far tail.

Slapak et al. (2012) suggested three main routes for ion outflow; (1) cold ion that will end up mainly in the plasma sheet (Mouikis et al., 2010; Haaland et al., 2012; Liao et al., 2015), (2) energised ions from the cusp to the plasma mantle (Liao et al., 2010; Slapak et al., 2017; Schillings et al., 2019), (3) energised ions from to cusp going directly to the magnetosheath (Slapak et al., 2017). Slapak et al. (2017); Slapak and Nilsson (2018); Schillings et al. (2019) suggested that ions observed in the plasma mantle have sufficient energy and velocity to escape in the distant tail. However, our results show that very few ions reach the distant tail but instead escape directly through the magnetopause after a few minutes (~ 17 min). These O^+ ions have short or middle length trajectories in our model (less than 2000 steps, see also Section 4) and represent 95% of our sample. Most (99.6%) of these O^+ ions reach a point where the tracing is stopped at a geocentric distance higher than 10 Re and escape the magnetosphere. For ions with trajectories longer than 2000 steps (5% of the total trajectories), 35% is earthward flow due to its interaction with the plasma sheet. Most of these ions do not return to the ionosphere. Some will instead experience charge exchange, become neutral and be lost from the magnetosphere. This assumption is supported by Ebihara et al. (2006), who modelled O^+ trajectories and introduce a charge exchange process in their model. They estimated that 2% of the total outflow became neutral due to charge exchange with the hydrogen geocorona. Other particles will drift to the magnetopause (magnetopause shadowing) and be lost. We note that ion precipitation recorded by the DMSP spacecraft (Newell et al., 2007) indicates a total precipitation of ions (H^+ and O^+) of the order $10^{24} s^{-1}$, which is most of the time dominated by cusp precipitation, not return flow precipitation. This is even less than the return flow estimated by Slapak and Nilsson (2018), indicating that most return flow indeed does not precipitate to the ionosphere. However, we do not study the fate of this earthward ion flow and therefore they are not considered as escaping ions in this study.

Under quiet magnetospheric conditions ($Dst \geq -20$ nT), it was found that 3% of the final positions of the trajectories is within a geocentric distance of 10 Re (return flow), whereas during disturbed conditions we observe only 1.6% return flow. This result agrees with Ebihara et al. (2006), who found that under quiet time 4% to 7% of the outflowing ions return to Earth. Under disturbed conditions, the authors estimated a smaller return of 0.6% to 0.8%.

Finally, since O^+ ions are launched from the plasma mantle, the particles observed by CODIF already went through transverse heating and centrifugal acceleration. Thus this model includes most of the energisation and acceleration compared to other models. Moreover, the model does not include wave-particles interaction after the oxygen ion has been launched.

6 Summary and conclusions

Based on previous suggestions that O^+ ions from the plasma mantle are escaping (Slapak et al., 2017; Slapak and Nilsson, 2018; Schillings et al., 2019), we investigate the fate of ions by tracing the particles forward in time in the magnetosphere. The magnetosphere is represented by the Tsyganenko T96 model for the magnetic field and the Weimer 2001 model for the electric field (ionospheric potential). We analyse 131 plasma mantle events detected automatically in the Cluster data during 2001 and

2007. For each event, 200 O⁺ ions with an initial parallel and perpendicular velocity are launched from the plasma mantle.
295 The initial velocities and positions are determined by Cluster observations and are used as inputs for the forward tracing. Our results are summarised in the following points:

1. The O⁺ ions observed in the plasma mantle have an initial parallel velocity **lower than the thermal velocity as expected. Thus, the thermal velocity dominates from the start, and through high perpendicular temperatures, the mirror force will increase the parallel velocity further downstream of the observation point.**
- 300 2. **98%** of the final positions (out of 26200) are located beyond a geocentric distance of 10 Re. These particles escape and are lost into the solar wind. 20% of the ions escape directly through the high-latitude dayside magnetopause.
3. **2%** of the total trajectories lead back towards earth, i.e. they constitute return flow. Some of these O⁺ ions have interacted with the plasma sheet in the distant tail and eventually end up between the Earth and a geocentric distance of 10 Re.
- 305 4. Under disturbed magnetospheric conditions (Dst < -20 nT), we observe **1.6 % return flow**, whereas during quiet time the return flow increases to **3%**.
5. We do not find any correlation between the IMF direction, the geomagnetic disturbances and the final positions of O⁺ in our tracing model. However, the ions ending up close to the Earth (geocentric distance smaller than 10 Re) are for 67% of the time associated with southward IMF.

Code and data availability. The Cluster data can be retrieved from the Cluster Science Archive <<https://csa.esac.esa.int/csa-web/>>. The
310 solar wind parameters (OMNI data) are provided by the Space Physics Data Facility (SPDF), <<https://omniweb.gsfc.nasa.gov/>>. The Dst index is provided by WDC for Geomagnetism in Kyoto <<http://wdc.kugi.kyoto-u.ac.jp/dstdir/>>. Finally, the tracing code is available for download at <<https://doi.org/10.5281/zenodo.3466771>>.

Author contributions. A.S. made the main analysis and wrote the manuscript. H.G and A.D.S. developed the tracing code. H.N., Y.E., L.G.W., M.Y. and R.S. participated actively in the discussion and the revisions. All authors contributed to the writing of the final manuscript.

315 *Competing interests.* The authors declare that they have no competing interests.

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