Ion escape from the high latitude magnetopause: analysis of oxygen and proton dynamics in the presence of magnetic turbulence

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Abstract. Recent Cluster observations of the vicinity of the high latitude magnetopause indicate the presence of beams of singly charged oxygen ions, which are of ionospheric origin. In this paper we examine the role of magnetic turbulence combined with a dc electric field across the magnetopause in causing the cross field transport of protons and of singly charged oxygen ions, by means of a kinetic test particle simulation. We find that the observed values of magnetosheath turbulence and electric fields can produce a substantial escape of the oxygen ions relative to protons. By varying the magnetic turbulence level in the simulation, we find that the number of O\(^+\) crossing the magnetopause grows with \(\delta B/B_0\), and that very few ions can cross the magnetopause for \(\delta B/B_0=0\). The ion temperature also grows with \(\delta B/B_0\), showing that magnetic turbulence is effective in thermalizing the kinetic energy gain due to the cross-magnetopause potential drop. We suggest that this mechanism can help to explain Cluster observations of energetic oxygen ions during a high-latitude magnetopause crossing.

Keywords. Magnetospheric physics (Magnetopause, cusp, and boundary layers) – Space plasma physics (Numerical simulation studies; Transport processes)

1 Introduction

It was suggested by Haerendel et al. (1978) that the magnetospheric regions above the polar cusps would correspond to strong perturbations of the magnetic and velocity fields. In situ measurements by, among the others, the Prognoz 8, Interball, Polar, and Cluster spacecraft have shown that this is indeed the case (Savin et al., 1998, 2002, 2005a; Nykyri et al., 2004, 2006; Sundkvist et al., 2005b). The strong turbulence observed could be due either to magnetic reconnection occurring at the high latitude magnetopause (Scudder et al., 2002), or to instabilities related to the shear flows in the magnetosheath, or to kinetic instabilities at frequencies around the local proton gyrofrequency (Sahraoui, 2006; Nykyri et al., 2006; Zimbardo, 2006). Magnetic turbulence in the cusp region exhibits a power spectrum which often has a double slope, with spectral index around 1.2–1.7 below the proton gyrofrequency, and around 2.5–4 above the proton gyrofrequency (Nykyri et al., 2006). Further, coherent structures like plasma bubbles and Alfvénic vortices are observed close to the cusp region (Sundkvist et al., 2005a; Savin et al., 2005a), with characteristic scales of the order of the proton gyroradius (drift-kinetic Alfvén vortices) (Sundkvist et al., 2005a). Bicoherence analysis shows that nonlinear 3-wave interactions are going on in the magnetopause (Savin et al., 2005b). In addition, the polar cusps are often populated with high energy particles, with energies up to a few MeV (Chen et al., 1998); the origin of these particles is still a matter of debate: the possibility that they are accelerated locally indicates that the cusps are regions of intense energy conversion, and that they can be an ideal laboratory for nonlinear plasma processes (Blecki et al., 2005).

On the other hand, singly charged oxygen ions, of ionospheric origin, are often observed in the magnetosphere (Shelley et al., 1972; Lockwood et al., 1985; Moore et al., 1986; Yau and Andre, 1997; Andre and Yau, 1997; Chappell et al., 2000; Peroomian et al., 2006). Recently, during several crossings of the high latitude magnetopause, Cluster observed O\(^+\) beams with energies of 10–20 keV (Bogdanova et

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In the present runs, the electric field is modeled as $E_x \equiv E_0 \exp[-(x-x_0)^2/\Delta^2]$, with $x_0 = 0.25 L$, that is the electric field is centered on the outward side of the magnetopause transition, in agreement with the observations (Amata et al., 2006) and with the fact that the quasi dc $E_x$ is due to $V \times B$ in the magnetosheath. For most runs, the peak value is $E_0 = 22.57 \text{ mV/m}$, which corresponds to a potential energy drop $\Delta U = e\Delta \varphi \approx 17 \text{ keV}$ within the simulation box. Another
where \( n \) phases \( \phi_k \) are also chosen so that the fluctuations sum up coherently for \( x = 0 \), so that they are stronger in the center of the simulation box (for more details, see Veltri et al., 1998, and Greco et al., 2003). The Fourier amplitudes \( \delta B(k) \) are given by

\[
\delta B(k) = \sum_{k, \sigma} \delta B(k)e_\sigma(k) \exp[i(k \cdot r + \phi_k^\sigma)],
\]

(1)

where \( e_\sigma(k) \) are the polarization unit vectors, and the random phases \( \phi_k^\sigma \) are chosen so that the fluctuations sum up coherently for \( x = 0 \), so that they are stronger in the center of the simulation box (for more details, see Veltri et al., 1998, and Greco et al., 2003). The Fourier amplitudes \( \delta B(k) \) are given by

\[
\delta B(k) = \frac{C}{(k_x^2l_x^2 + k_y^2l_y^2 + k_z^2l_z^2 + 1)^{\alpha/4 + 1/2}}
\]

(2)

where \( C \) is a normalization constant, which sets the value of the magnetic turbulence level. The wave vectors are chosen on a discrete 3-D grid, with \( k_i = 2\pi n_i/l_i \), \( i = x, y, z \), where \( n_i \) are the harmonic numbers and \( l_i \) the turbulence correlation lengths. We set \( l_x = 0.05L_x \) and \( l_y = l_z = 0.5L_x \) (this also corresponds to the simulation box geometry).

For all runs, 20,000 particles were injected at \( x = -0.5L_x \), which represents the magnetospheric side of the simulation box, with random position in the \( yz \) plane. The injection velocity corresponds to a thermal velocity of 600 eV and a bulk velocity 50–100 km/s, making an angle of about 40° with the average magnetic field direction at the \( x = -0.5L_x \) boundary. Protons were injected with the same initial flow velocity and the same initial temperature. The trajectories of test particles are integrated by means of a 4th 5th order adaptive step Runge-Kutta routine. A maximum integration step corresponding to the minimum between 0.1\( \Omega_i^{-1} \) and 1/10 of the time needed to cover the shortest wavelength of the turbulence model was chosen. Here, \( \Omega_i \) is the ion gyrofrequency. We checked the integration accuracy by requiring that the particle energy be conserved with a relative variation of at most \( 10^{-6} \), and typically much less. Distribution function moments like density \( n \), bulk velocity \( V \), and temperature \( T \) are computed on a 3-dimensional grid in space (Veltri et al., 1998; Greco et al., 2003).

It was shown by Taktakishvili et al. (2003) and by Greco et al. (2003), that this magnetic turbulence allows the flow of ions across the magnetopause, for magnetic fluctuations levels \( \delta B/B_0 \geq 0.3 \). Here, \( \delta B \) is the rms value of the fluctuations; we note that in the cusp region values of \( \delta B/B_0 \) of order of 0.5–1 are not uncommon. During the magnetopause crossing of 13 February 2001, upstream in the magnetosheath and at the magnetopause \( \delta B/B_0 \sim 0.3–0.4 \), see Fig. 1. The magnetic fluctuations were strong in the frequency range \( 10^{-2}–1 \) Hz (Nykyri et al., 2006), and we note

\[
\frac{\delta B}{B_0} = 0.3–0.4
\]
that the O⁺ gyrofrequency in the 50 nT magnetic field at the magnetopause is ν = 4.7 x 10⁻² Hz. This resonant interaction corresponds in the simulation to the fact that the oxygen Larmor radius (~300 km) falls within the range of the turbulence wave lengths in the x-direction (160 km < λ < 2000 km). Clearly, the proton behaviour can be different because of the smaller Larmor radius.

3 Simulation results

In this section we present the results of the simulation, compare oxygen and proton trajectories and present the cross-magnetopause profiles (along the x-direction) of their number density, bulk motion velocity, and kinetic temperature. Then we investigate in more detail the influence of the magnetic turbulence level and of the electric field value on the oxygen transport.

3.1 Proton vs. oxygen comparison

In Fig. 2 the xz projections of sample oxygen and proton trajectories are presented. In this figure, oxygen is represented by black solid lines and protons by lighter gray lines. For each of the panels both ion species were launched with the same initial position, i.e., the same randomly chosen y and z coordinates at the magnetospheric border of the simulation box, x = -0.5 L (bottom section of each panel). The upper part of each panel, x ≥ 0.5 L, represents the magneto-tosheath part of the simulation box. The upper panel of Fig. 2 shows reflected ions, that is, ions which exit the simulation box from the same side as the injection one. The middle panel shows particles that exit from the flank of the simulation box: both proton and oxygen exit from the z border at z = 30 L. Note that since the initial temperatures of the particles are equal, the proton gyroradius is 4 (square root of mass ratio) times smaller than the oxygen gyroradius. For both ion species, the magnetic turbulence causes a strong deviation from the idealized helical trajectories in simple magnetic field geometries. The protons have a smaller gyroradius and thus are tied more strongly to the magnetic field structure, so that they exhibit a much more stochastic trajectory. Indeed, it can be shown that for large Larmor radii, part of the magnetic fluctuations are averaged along the gyroorbit (Zimbardo, 2005; Pommois et al., 2007). On the other hand, the O⁺ acceleration by the electric field from the middle (x ~ 0) of the simulation box is rather obvious. Both ion species spend most of the time in the central part of the box x ~ 0 before exiting, exhibiting a rather prominent average electric drift motion (E x B) in the positive z-direction in the upper section (x > 0), which is the reason of their exit from the simulation box at z = 30 L. The bottom panel of Fig. 2 shows a different behavior of the oxygen and proton ions. The oxygen is strongly accelerated in the initial phase in the cross magnetopause direction by the electric field, and after bouncing close to the region of the strong border magnetic field x = 0.5 L, finally penetrates into the magnetosheath. On the contrary, proton remains all the time close to magnetosphere boundary and finally exits from the simulation box border in the y-direction, y = 15 L (see the inset in this panel, showing the projection of the proton trajectory on the x-y plane). Note that E_x is exponentially small for x < 0, so that the (E x B) velocity is negligible. These trajectories are most interesting, since they demonstrate the fact that oxygen ions, having larger gyroradius, have more chances to cross the magnetopause and be accelerated by the electric field than protons.

This behaviour is confirmed by Fig. 3, which shows the density, normalized to the injection value at x = -0.5 L, as a function of x for the level of fluctuations δB/B₀ = 0.6. In this and the following figures, the plotted quantities are averaged over the y- and z-directions. It can be seen that a larger number of oxygen ions are able to cross the magnetopause, while proton density drops dramatically for the rightmost, magnetosheath side of the simulation box, x > 0. In spite of
the substantial level of magnetic turbulence, very few protons are able to cross the magnetopause.

Figure 4 shows the z-component $V_{bz}$ of oxygen and proton bulk motion, for the level of fluctuations $\delta B/B_0=0.6$. The bulk velocity $V_{bz}$ is increasing with $x$, because of the acceleration due to $E_x$ for both species. Protons appear to be faster, but oxygen ions gain bulk energy more efficiently, due to their larger mass. The behaviour of bulk energy can be inferred from Fig. 4, where it is seen that the oxygen velocity is about one half of the proton velocity, at the right boundary of the simulation box. Due to the mass ratio, this implies that the oxygen bulk energy is about 4 times the proton bulk energy (a minor contribution comes from $V_{by}$, not shown).

This means that in the presence of turbulence ions can cross the magnetopause, but those ions which have larger gyroradius cross quickly and easily, so that they gain an increase of bulk kinetic energy.

Figure 5 shows the temperature growth with $x$ for both particles, normalized to the potential energy drop $\Delta U$. One can see that magnetic fluctuations are an active thermalizing agent. These profiles show more efficient proton heating due to the fact that the fluctuations scatter protons more strongly, causing them a wider spread in particle velocity, which corresponds to an increase in temperature. Conversely, for oxygen ions a larger share of energy goes into bulk kinetic energy rather than thermal energy.

These results show that the turbulent magnetopause exhibits a selective permeability for ions with different masses, allowing heavier oxygen ions to exit from the magnetosheath, and be accelerated and heated by the electric field. For protons, on the contrary, the magnetopause appears to be a much more impermeable obstacle, since their smaller gyroradius does not allow them to move across the turbulent magnetopause efficiently.

3.2 Influence of the turbulence level $\delta B/B_0$

We made a number of runs with oxygen ions only, in order to assess the influence of $\delta B/B_0$ and of $E_0$ on the transport properties. Figure 6 shows the density profile for $O^+$, for turbulence levels varying from $\delta B/B_0=0$ to 0.3, 0.6, and 1.0, i.e., in the range of those observed at the high latitude magnetopause. While the left side (the injection side) of the density profiles reflects the ion penetration due to the initial Larmor radii (which have an approximately Gaussian distribution), the right side depends on the turbulence level, which is the basic ingredient which allows cross field transport. It can be seen that the height of the density profile increases with the
turbulence level, in agreement with the results of Greco et al. (2003). Also note that, in practice, almost no oxygen ion is able to cross the current layer for $\delta B/B_0=0$.

Figure 7 shows the behaviour of the $x$ component of bulk velocity, $V_{bx}$. Such a velocity increases with $\delta B/B_0$, and corresponds to the flux of ions from the injection (magnetospheric) side at $x=-0.5L$ to the magnetosheath side at $x=0.5L$, with the asymmetry from the negative to positive values of $x$ due to the fact that the electric field is centered at $x_0=0.25L$. We point out that the values of the velocity are very small, a few km/s, which is much smaller than the particle velocities. This means that, in spite of the large gyroradius, $O^+$ motion occurs in a diffusive way.

Figure 8 shows the $z$ component of bulk velocity, $V_{bz}$. It can be seen that it grows from negative to positive values of $x$, and that $V_{bz}$ is the larger, the smaller $\delta B/B_0$. For small $\delta B/B_0$, values of $V_{bz}$ of the order of 300–400km/s are obtained; these large values are due to the $z$-component of the $E \times B$ drift, given by $V_{Ez}=E_x B_y/B^2$. Since $B_y=\text{const}$, the value of the drift velocity depends mostly on $E_x$, which is strongest in the magnetosheath side, and with some modulation by $B^2$. We also notice that the obtained values of $V_{bz}$ are larger than those observed because, in the present runs, $E_x$ is larger than that observed, too. On the other hand, when the turbulence level is increased, the particle trajectories are
disturbed, and important deflections are caused by $\delta B$, see Fig. 2, so that the $E \times B$ motion is progressively blurred out, and $V_{bz}$ decreases. A somewhat similar behaviour is found for $V_{by}$ (not shown). Note that for large $\delta B/B_0$, a smaller fraction of the potential energy due to $E_x$ is converted to bulk motion.

Figure 9 shows the corresponding temperature profiles. It can be seen that the temperature increases from the magnetospheric to the magnetosheath sides, and that the larger $\delta B/B_0$, the larger the temperature. For the kinetic energy of bulk motion, the opposite trend with $\delta B/B_0$ is found (not shown). This confirms that magnetic turbulence plays an important role in thermalizing the kinetic energy obtained by crossing the electric potential drop. As shown by Fig. 5, such a thermalization is more effective for H$^+$ than for O$^+$.

3.3 Influence of the electric field strength $E_0$

We explored the influence of the steady electric field intensity on the transport and energization properties of O$^+$, changing the value of the peak electric field from $E_0=0$ to 6 mV/m and to 22 mV/m, while keeping the magnetic turbulence level to $\delta B/B_0=0.6$. Figure 10 shows the oxygen density profile for different electric fields: it can be seen that the density decreases with the increase of $E_0$, contrary to naive expectations. We consider that this is due to the influence of the $E \times B$ drift, which grows with $E_0$ and which causes the ions to move fast in the y- and z-directions. Indeed, in a stationary one dimensional configuration, the continuity equation requires the flux to be constant, so that the larger the velocity, the smaller the density. Accordingly, the density at around $x=0$ is maximum for $E_0=0$, as there is no electric drift and ions lazily spend time in the center of the simulation box, finding their stochastic pathway through the distorted magnetic field. The influence of $E_0$ is clearly shown in Fig. 11, where the bulk velocity $V_{bz}$ is reported, and it is seen that $V_{bz}$ steadily increases with $E_0$, in spite of the relevant turbulence level $\delta B/B_0=0.6$. Finally, in Fig. 12 we show the temperature profile for different values of $E_0$. All temperatures are normalized to the largest potential energy drop $\Delta U$ corresponding to $E_0=22$ mV/m. As expected, the stronger $E_0$, the larger the temperature increase due to the crossing of the potential drop. For $E=0$, there is no temperature growth, apart from a very small increase which can be related to velocity filtration.
4 Conclusions

We propose that the magnetic fluctuations can be effective in allowing particles to migrate across the magnetopause current layer. We performed a comparative numerical analysis of oxygen and proton ion dynamics in the Earth’s magnetopause in the presence of magnetic turbulence and cross magnetopause electric field. The fluctuations and the finite Larmor radius effect allow ions to jump from one magnetic surface to another, gradually being displaced in the cross layer (X) direction. The simulation clearly demonstrates how the mass (Larmor radius) difference between the two species results in a substantial dissimilarity in particle dynamics and, consequently, in difference of the cross-magnetopause profiles of the distribution function moments, such as density, bulk velocity, and temperature. It appears that heavier oxygen ions are more likely to exit from the magnetosheath and be orderly accelerated by the electric field. Protons, due to their smaller gyro radius, are hardly able to cross the magnetopause, being effectively scattered by the magnetic fluctuations and heated. The reported results of a selective permeability of the turbulent magnetopause could be used to explain the Cluster observation of energetic oxygen ions on 13 February 2001, and show that oxygen ions can escape locally from the magnetopause. Analysis of Cluster data in the magnetotail, too, shows that the proton and singly charged oxygen dynamics can be very different (Kistler et al., 2005), with the O\(^{+}\) ions exhibiting a nonadibatic behaviour.

By varying the magnetic turbulence level in the simulation, we have shown that the number of O\(^{+}\) crossing the magnetopause grows with \(\delta B/B_{0}\), and that very few ions can cross the magnetopause for \(\delta B/B_{0}=0\). The ion temperature also grows with \(\delta B/B_{0}\), showing that magnetic turbulence is effective in thermalizing the kinetic energy gain due to the cross-magnetopause potential drop. It appears that this potential drop may give a contribution to the oxygen energetization, although additional mechanisms have to be considered in order to reach the 10–20 keV of the observed O\(^{+}\) beams (e.g., Andre and Yau, 1997; Yau and Andre, 1997; Chappell et al., 2000; Bogdanova et al., 2004; Nilsson et al., 2006). On the other hand, populations of very energetic ions with energies from 10 keV up to a few MeV are often observed in the cusp regions as well (Chen et al., 1998; Chen and Fritz, 2001; Fritz et al., 2003). The acceleration mechanisms for these particles are not yet clear (Chen et al., 1998; Fritz et al., 2000), although electromagnetic turbulence is likely to play an important role. This issue will be considered in a future paper.

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