Low-Energy Ion Escape from the Terrestrial Polar Regions

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Abstract

The contemporary terrestrial atmosphere loses matter at a rate of around 100,000 tons per year. A major fraction of the net mass loss is constituted by ions, mainly H` and O`, which escape from the Earth’s ionosphere in the polar regions. Previously, the outflow has only been measured at low altitudes, but to understand what fraction actually escapes and does not return, the measurements should be conducted far from the Earth. However, at large geocentric distances the outflowing ions are difficult to detect with conventional ion instruments on spacecraft, since the spacecraft electrostatic potential normally exceeds the equivalent energy of the ions. This also means that little is known about the ion outflow properties and distribution in space far from the Earth.

In this thesis, we present a new method to measure the outflowing low-energy ions in those regions where they previously have been invisible. The method is based on the detection by electric field instruments of the large wake created behind a spacecraft in a flowing, low-energy plasma. Since ions with low energy will create a larger wake, the method is more sensitive to light ions, and our measured outflow is essentially the proton outflow.

Applying this new method on data from the Cluster spacecraft, we have been able to make an extensive statistical study of ion outflows from 5 to 19 Earth radii in the magnetotail lobes. We show that cold proton outflows dominate in these large regions of the magnetosphere in both flux and density. Our outflow values of low-energy protons are close to those measured at low altitudes, which confirms that the ionospheric outflows continue far back in the tail and contribute significantly to the magnetospheric content. We also conclude that most of the ions are escaping and not returning, which improves previous estimates of the global outflow. The total loss of protons due to high-latitude escape is found to be on the order of 10^20 protons/s.

Keywords: space physics, ion outflow, polar wind, auroral upflows, atmospheric escape, magnetotail lobes, spacecraft wake, electric field measurements

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Measure what is measurable, and make measurable what is not so.

Galileo Galilei (1564-1642)
List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.


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Chapter 1

Introduction

The Earth’s atmosphere constantly loses matter to the surrounding space through different outflow processes. From the ionized upper part of the atmosphere – the ionosphere – outflows occur at high latitudes above the geomagnetic poles. The ions in the ionosphere escape along "open" magnetic field lines extending anti-sunward to large distances from the Earth (see Figure 1.1). Above the geomagnetic poles, the ion outflow is constituted by the low-energy polar wind, which carries the light ions H\textsuperscript{+} and He\textsuperscript{+} away. At slightly lower latitudes (around 70°) the fascinating spectacle of aurora is common. The aurora is the visible result of a series of energization mechanisms in the near-Earth space. These mechanisms can energize ions in the upper ionosphere, transporting away also species of higher mass (mainly O\textsuperscript{+}).

The outflows continue out into the magnetosphere, which is the region in near-Earth space where the motion of charged particles is dominated by the Earth’s magnetic field. Following the paper by Chappell et al. (1987), who claimed that the ionosphere could be an adequate source of plasma, i.e. ionized gas, to the magnetosphere, there was a vivid debate around the origin of magnetospheric plasmas for more than a decade. Those who believed that the Sun was the only significant contributor to magnetospheric plasmas referred to global simulations (e.g. Ashour-Abdalla et al., 1992), as well as observations of correlation between the solar wind and the density in the plasma sheet – the central part of the tail of the magnetosphere (Borovsky et al., 1998). Other observations showed instead the existence of high-energy oxygen and helium ions in the plasma sheet (e.g. Shelley et al., 1972; Chappell et al., 1987) indicating that the ionosphere at least at times is the origin of a significant part of the magnetospheric plasma. Outflows with energies below a few tens of electronvolts account for the most important part of the ionospheric escape in terms of supply of particles to the magnetosphere (Paper V of this thesis). Measurements of low-energy ion outflows at low altitudes in combination with computer simulations have proposed that large amounts of ions will travel out
to far distances and fill the magnetospheric tail (e.g. Chappell et al., 2000; Huddleston et al., 2005). To confirm the simulation results and show that all outflowing ions observed at low altitudes actually escape from the Earth and do not return, measurements should be conducted farther away from the Earth. However, at high altitudes the low-energy ions are difficult to measure with conventional ion detectors, and until now there has been no clear evidence from measurements *in situ* for the continuation of the low-energy outflows far from the Earth.

![Figure 1.1](image.png)

*Figure 1.1:* Schematic picture of different outflows from the Earth’s ionosphere out into the magnetosphere. The most important ion outflow mechanisms are shown: the polar wind over the polar caps, upwelling ions (UWI) in the cleft, creating the cleft ion fountain, and auroral upflows from the auroral oval. These different processes are described in Section 3.2. (After Hultqvist et al., 1999, with kind permission from Springer Science and Business Media.)

In this thesis, we present a new method to measure the low-energy proton outflows with the Cluster spacecraft at several Earth radii ($R_E$) away from the Earth.\(^1\) Since this method allows us to measure much farther away than previous spacecraft missions, we are able to give a better estimate of the global proton outflow than ever before. We have also for the first time with spacecraft

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\(^1\)The nominal value of the radius of the Earth is 6371.2 km.
measurements confirmed that large parts of the magnetosphere consists of cold, tenuous and previously invisible plasma originating in the ionosphere.\footnote{Here we define \textit{cold} as temperatures on the order of a few eV and \textit{tenuous} as densities on the order of tenths of particles/cm$^{-3}$.}

In addition to the ion outflows, the atmosphere vanishes through charge exchange between energetic magnetospheric ions and atmospheric neutrals, as well as through thermal escape of light ions, predominantly hydrogen atoms. In thermal outflows the high-energy tail in the thermal distribution is allowed to escape the Earth’s gravitational field. These outflows constitute a significant part of the total escape from the Earth. The total loss rate of the atmosphere is around a few kilograms per second.

While the particles participating in the outflows are ultimately lost from the total Earth-atmosphere system, the atmosphere can be resupplied by internal sources, \textit{e.g.} the oceans or volcanos. The Earth also accretes matter from impacts with interplanetary bodies, at a rate which is on the same order of magnitude as the loss. In addition, the current terrestrial mass loss is vanishingly small in comparison to the total mass of the atmosphere. However, the outflow was probably much more elevated when the Sun was young and the solar wind stronger and could have played a significant role for the early development of the Earth’s atmosphere. The outflow processes are also important for the understanding of the evolution of atmospheres on other planetary objects.

The thesis is structured as follows: In Chapter 2 we describe some basic principles of plasma physics and the space environment around the Earth. In the following two chapters we investigate the different escape processes, as well as estimate the accretion of interplanetary matter to the Earth. In Chapter 5 we review important measurements of ionospheric plasma in different regions of the magnetosphere. We also describe various mechanisms driving the outflow and the final destiny of the ions. Chapter 6 is devoted to our new method and electric field measurements, on which the method relies. In Chapter 7 we give a summary of the five scientific papers comprised in this thesis, and in the subsequent chapter a summary of the most important findings of this thesis is given. Finally, there is a summary in Swedish.
Chapter 2

The space environment

Phenomena in the sky have fascinated mankind for millennia. Four hundred years ago the Italian scientist Galileo Galilei invented the telescope, and since then it has revealed some of the mysteries of our solar system, galaxy and the whole universe. Nevertheless, it was not until the satellite era, which started with the launch of the Soviet satellite Sputnik 1 in 1957, that it was possible to explore the near-Earth space environment in detail. An adequate description of this environment is necessary to understand such a common and relatively close phenomenon as the aurora. This chapter is intended to give a brief introduction to space plasma and the space environment around us, from the outer magnetosphere down to the upper atmosphere. We will focus on composition and processes in the atmosphere and ionosphere, since this is where escape of ions and neutral atoms originate. For a more detailed description of the space environment, books on space and atmospheric physics, e.g. Kivelson and Russel (1995), Gombosi (1998) and Visconti (2001), are recommended.

Figure 2.1: Aurora in the Swedish mountain scenery as seen by the invisible being Plupp. (After Borg, 1996, with kind permission from Opal.)
2.1 Properties of a plasma

Plasma is an ionized gas, in which the atoms are dissociated into electrons and positive ions. It is the dominating state of baryonic matter in the universe, estimated to comprise around 99% of all observable matter. Because of this abundance of plasma in the universe, we will need knowledge in plasma physics to understand phenomena in space. Here we present some basic principles of plasma physics, which will help in the understanding of the phenomena described in this thesis.¹

One important feature of a plasma is that it will exhibit collective behaviour, which means that the plasma particles will be governed by the long-range electromagnetic forces originating from their average motion. This is in contrast to a normal gas, where the particle motion is determined by collisions. The phenomenon of Debye shielding is a fundamental property of a plasma and gives an example of collective behaviour. When a charged object is immersed in a plasma, the potential around it will be shielded out by the motion of the ions and the electrons. A positively charged object will attract a cloud of electrons and repel ions, while a negatively charged object will be enclosed in a cloud consisting mainly of ions. If the plasma has very low temperature, the shielding will be almost perfect outside the cloud. For warmer plasmas, however, the small potentials at the edge of the clouds, will not be able to prevent the electrons or ions from escaping. To get a notion of the size of the shielding cloud, we introduce the Debye length, which is a characteristic length for the shielding of the potential around a charged object. The Debye length, \( \lambda_D \), is defined by the expression

\[
\lambda_D = \sqrt{\frac{\varepsilon_0 K T_e}{n q_e^2}},
\]

where \( \varepsilon_0 \) is the constant of permittivity, \( K \) the Boltzmann constant, \( T_e \) the electron temperature, \( n \) the plasma density² at infinity and \( q_e \) the electron charge.

It is worthwhile to note that the Debye length will increase when the temperature increases, which can be explained by the fact that the augmentation of the thermal motion of the plasma particles will make the shielding weaker. Conversely, a dense plasma will make the Debye length shorter, as there are more particles to shield out the potential. Debye shielding is for example of importance, when considering spacecraft-plasma interactions and measurement of low-energy plasmas. A criterion for a plasma is that it is quasineutral, i.e. that the electron density is approximately equal to the ion density \( (n_e \approx n_i \approx n) \). This is fulfilled when the characteristic length scale of a physical phenomenon is much larger than the Debye length. In such a case, every local concentration

¹For a more thorough description, Chen (1984) gives a good introduction to plasma physics. This book is used as the main reference for this section.

²The plasma density is expressed in particles per unit volume.
of charge will be cancelled out in a distance much smaller than the characteristic length scale.

Considering only the individual plasma particles, we can find some useful relations for their motion in electromagnetic fields, here taken to be constant both in time and space. The equation of motion for a particle with mass $m_\alpha$, charge $q_\alpha$ and velocity $v_\alpha$ under the influence of an electric field $E$, and a magnetic field $B$ is given by

$$m_\alpha \frac{dv_\alpha}{dt} = q_\alpha(E + v_\alpha \times B).$$

(2.2)

If the electric field is zero ($E = 0$) and $v_\alpha$ is perpendicular to $B$, equation 2.2 just describes a circular motion with the Lorentz force as the central force ($F_c = q_\alpha v_\alpha \times B$). The angular frequency of this motion is the *cyclotron angular frequency*, $\omega_c = \frac{|q_\alpha B|}{m_\alpha}$, and the radius is the *Larmor radius*, $r_L = \frac{v_\alpha \perp}{\omega_c} = \frac{m_\alpha v_\alpha \perp}{|q_\alpha B|}$. If the velocity has a component along the magnetic field, the particle will move in a spiral. The projection of the motion onto the plane perpendicular to $B$ will, however, still be a circle with the same centre as before. As can be seen in Figure 2.2, for non-zero electric fields all particles, independent of charge, will drift perpendicular to both the electric and magnetic fields. The drift velocity is $u = E \times B / B^2$, and this motion is refereed to as $E \times B$-drift. There is no drift along the magnetic field unless there is a parallel electric field, but in space plasmas the mobility of electrons is normally so high that such electric fields can not be maintained. Exceptions can be found in the auroral regions, where parallel electric fields can accelerate particles to very high energies.

![Figure 2.2](image_url): In the presence of electric and magnetic fields, ions and electrons will drift in a direction perpendicular to both the electric and magnetic fields. The drift velocity is given by $u = E \times B / B^2$ and is independent of both charge and mass of the particle.
Another effect of the high conductivity in space plasmas, is that the magnetic field lines can be regarded as following the plasma motion if time variations are small. The magnetic field lines are then referred to as frozen-in field lines. The volume bounded by a set of field lines is called a flux tube, and the frozen-in condition implies that particles initially linked to a certain flux tube remains fixed to it throughout the plasma motion. The frozen-in condition is satisfied if the plasma motion can be approximated by

\[ \mathbf{E} + \mathbf{v} \times \mathbf{B} \approx 0, \]

where \( \mathbf{v} \) is the velocity of the plasma, which will be equivalent to the single particle drift for non-zero electric fields, \( \mathbf{E} \times \mathbf{B} / B^2 \). For many applications in space physics, such as the description of plasma convection in the magnetosphere, the frozen-in condition is a very useful approximation.

Because of the electromagnetic properties of plasma, different types of oscillations will arise. The simplest type is the plasma oscillations. The light electrons will, because of their inertia, oscillate back and forth against a uniform background of massive immobile ions, with a characteristic frequency, the plasma frequency. The plasma frequency, \( \omega_{pe} \) is given by

\[ \omega_{pe} = \sqrt{\frac{n_0 e^2}{\epsilon_0 m}}. \]

The quantity \( \omega_{pe}^{-1} \) is often chosen as a characteristic time scale for plasmas.

### 2.2 The magnetosphere

The existence of the Sun is necessary, either directly or indirectly, for all life on the Earth. As everybody knows, energy is transported from the Sun in form of electromagnetic radiation, which among others will give us enough heat and light and allow plants to grow. What is less known, is that the Sun does not only emit light, but also a high-speed stream of particles, at a rate of a million tons/s. This stream of plasma is called the solar wind. The solar wind plasma originates in the outer layers of the Sun, thus consisting mostly of protons, electrons and a small amount of helium ions. Some of these particles will eventually reach the Earth, but this is only a tiny fraction of all the particles in the solar wind, since the Earth is shielded by its magnetic field. This magnetic shield protects us from the highly energetic solar wind plasma, which has an average speed of 450 km/s and temperature of 100,000 K.

The solar wind is deflected around the Earth’s magnetic field, compressing it in the sunward direction and extending it in the anti-sunward direction (see Figure 2.3). Since the solar wind is supersonic at the Earth’s orbit, a shock
wave will form around the Earth reducing the speed of the solar wind plasma to subsonic values. This happens at the bow shock. Shocked solar wind particles continue into the magnetosheath, a turbulent region just outside the magnetopause, which is the border to the Earth’s magnetosphere. The solar wind experiences difficulties to enter the magnetosphere through the magnetopause. However, in the cusp regions the magnetopause is locally open, which will allow solar wind plasma to penetrate the magnetosphere. Behind the Earth the magnetotail extends to large geocentric distances. In the center of the tail the hot and low-density plasma sheet is located. The plasma sheet is separated from the tail lobes by the plasma sheet boundary layer. Outside the tail lobes, the high-density plasma mantle is found. The tail lobes are connected on open magnetic field lines to the polar caps – two approximately circular areas above the geomagnetic poles. Ionospheric plasma in these regions will escape along the magnetic field lines and fill the tail lobes with cold tenuous plasma. At lower latitudes, ions from the ionosphere will supply the plasmasphere, which is a cold and dense torus-shaped region confined within closed magnetic field lines. The polar caps are bounded by the auroral regions at around 70° northern and southern latitude. Here the aurora appears, when
charged particles (mostly electrons) from the magnetosphere enter the Earth’s atmosphere and collide with atoms and molecules, typically at an altitude of 100 km. In the collisions, the atmospheric atoms and molecules will be excited, and when de-excited, light will be emitted. This light can be seen in the sky at clear nights.

2.3 The atmosphere and ionosphere

2.3.1 The atmosphere

The Earth’s atmosphere is divided into different layers characterized by their temperature gradients (see Figure 2.4): the troposphere, the stratosphere, the mesosphere, the thermosphere and the exosphere (e.g. Strobel, 2002). The troposphere is closest to the Earth’s surface, and contains more than 80% of the atmospheric mass. When crossing the tropopause (the boundary between the troposphere and the stratosphere) the temperature changes from decreasing to increasing with altitude. The heating arises in the ozone cycle, where O$_3$ absorbs solar radiation, dissociates into oxygen atoms and O$_3$ is regenerated by the reaction O + O$_2$ → O$_3$, which releases heat. The stratosphere contains most of the atmosphere’s ozone, which is crucial for most of the Earth’s existing life forms, since it absorbs the Sun’s high-frequency ultraviolet (UV) light. Above the stratosphere lies the mesosphere, and the two regions are separated by the stratopause. In the mesosphere, the temperature gradient is again negative, due to CO$_2$ infrared cooling (Strobel, 2002). The upper boundary of the mesosphere is the mesopause, which is followed by the thermosphere, where the temperature rises rapidly (10-20 K/km) at low altitudes, but approaches a constant temperature at higher altitudes.

The thermosphere pass into the exosphere at the exobase, which is located at around 450 km. The exobase is defined as the boundary where the mean free path approximately equals the atmospheric scale height. The mean free path is the distance an atom or molecule travels without collisions, and the scale height is the distance over which the atmospheric pressure decreases by a factor of $e$. Each atmospheric constituent has its own scale height defined by

$$H_\alpha(h) = kT/m_\alpha g(h),$$

where $T$ is the temperature, $m_\alpha$ the mass of the species and $g(h)$ the altitude-dependent gravitational constant. The exosphere is of great importance for neutral escape from the Earth and will be treated in more detail in Section 3.1.

The atmosphere can also be divided into two separate regions: the homosphere, where turbulent mixing distributes the atmospheric constituents homogenously, and the heterosphere, where the species are not well mixed. The two regions are separated by the homopause at around 100 km (close to the
2.3. THE ATMOSPHERE AND IONOSPHERE

The atmosphere and ionosphere are divided into different layers based on temperature and electron density distributions. In the atmosphere, the layers are separated by temperature gradients, while in the ionosphere, different electron densities define the layers.

In a simple model, the density in the heterosphere can be given by an exponential decrease depending on the altitude, \( h \), and the scale height, \( H_\alpha \) (Shizgal and Arkos, 1996):

\[
n_\alpha = n_0 \exp \left( -\frac{h - h_0}{H_\alpha(h_0)} \right),
\]

where \( n_0 \) is the density of the species at the reference altitude \( h_0 \). This gives an accurate description when the temperature is independent of altitude.

The dry atmosphere consists of 78.1% nitrogen (N\(_2\)), 20.9% oxygen (O\(_2\)) and small amounts of other gases listed in Table 2.1 (Wayne, 1991; Visconti, 2001). In addition to these gases, over all altitudes in the atmosphere the water vapour content is 0.40%, while it is 1-4% closer to the surface. In the low atmosphere, hydrogen mainly appears as water vapour, while at higher altitudes it is first present in the compounds OH, HO\(_2\), and H\(_2\), and finally at the mesopause the principal form is atomic hydrogen (Hunten, 2002).

As explained above, O and O\(_2\) is transformed to O\(_3\) through photochemistry processes in the stratosphere. Higher up, atomic oxygen becomes more and more important and is the dominant atmospheric constituent in the thermosphere, where the photodissociation of O\(_2\) is fast, while recombination is slow.


<table>
<thead>
<tr>
<th></th>
<th>N₂</th>
<th>O₂</th>
<th>Ar</th>
<th>CO₂</th>
<th>Ne</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>78.1%</td>
<td>20.9%</td>
<td>0.93%</td>
<td>0.034%</td>
<td>0.018%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>He</th>
<th>CH₄</th>
<th>H₂</th>
<th>N₂O</th>
<th>O₃</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5.2 ppm</td>
<td>1.7 ppm</td>
<td>0.53 ppm</td>
<td>0.3 ppm</td>
<td>0.01-0.1 ppm</td>
</tr>
</tbody>
</table>

Table 2.1: Composition of the dry atmosphere (Wayne, 1991; Visconti, 2001). The compounds in green are the major greenhouse gases. The dominating greenhouse gas, water vapor, is not included in this table of the composition of the dry atmosphere, but the overall content is around 0.4%.

Only through diffusion downwards to the region around the mesopause, where hydrogen compounds work as catalysts, atomic oxygen can be recombined to O₂. Atomic nitrogen, on the other hand, does not exist in abundance in the thermosphere, since the N₂ bond is more difficult to break directly and the molecule is rapidly regenerated through the reaction N + NO → N₂ + O (Strobel, 2002).

The atmospheric density at sea level is 1.2 kg/m³, which corresponds to a number density on the order of 10²⁵ molecules/m³. The density decreases to 0.7 kg/m³ at the tropopause, to 0.03 kg/m³ at the stratopause, and to 0.0001 kg/m³ at the mesopause (Picone et al., 2002). In Figure 2.5 the altitude dependence of the number density of the most important atmospheric species can be found. The total mass of the atmosphere is estimated to 5 × 10¹⁸ kg (Wayne, 1991).

On the terrestrial planets Venus and Mars, the dominant species in the atmosphere is not N₂, but CO₂. With the emergence of life on the Earth, CO₂ was removed from the atmosphere and N₂ became the most important constituent. The Earth would have had a carbon dioxide dominated atmosphere today, if either life had never appeared or the temperature and pressure were elevated. The ratio N₂/CO₂ is in fact comparable on Earth and Venus, but almost all of the CO₂ content on Earth is sequestered in sedimentary rocks. With surface conditions comparable to Venus, the CO₂ would be released, along with evaporation of the oceans, creating an even denser atmosphere than that of Venus (Strobel, 2002). The early atmosphere of the Earth is also believed to show similarities to the N₂ rich atmosphere of Saturn’s moon Titan. This atmosphere contains the simplest building blocks for amino acids, such as HCN, and could potentially give clues about the formation of life on the Earth. This is one of the motivations for the exploration of Titan by the Cassini-Huygens mission (Mahaffy, 2005).
2.3. THE ATMOSPHERE AND IONOSPHERE

2.3.2 The ionosphere

2.3.2.1 General properties

The upper part of the neutral atmosphere is partly ionized mainly by solar UV light. At altitudes above 70 km, the UV intensity is high and collisions are so rare that the recombination rate is slow, resulting in the formation of a permanently ionized region in the upper atmosphere. This is the ionosphere.

The ionosphere has been probed by numerous rocket and satellite instruments, as well as by radar experiments. Figure 2.5 shows the composition of the sunlit ionosphere. Since the ionosphere is produced mainly by solar radiation, there is a substantial difference between the dayside and nightside ionosphere (see Figure 2.4). There are also large variations during the 11-year solar cycle, as well as seasonal variations at different latitudes.

As can be seen in Figure 2.5, there is a clear peak in the electron density at around 250 km. At higher altitudes, the ionization rate is lower due to decreasing neutral density, whereas below this altitude the intensity of the ionizing radiation decreases. In addition to the peak, there are also substructures in the electron density, and the early observers divided the ionosphere into three different regions: The D layer below 90 km, the E layer between 90 and 130 km, and the F layer above 130 km (see Figure 2.4). During daytime the F layer can be further decomposed into the F1 and F2 layers. The main peak is within the F2 layer, while the F1 layer lies below with a peak at around 170 km.

![Figure 2.5: Composition of species in the sunlit ionosphere and the neutral atmosphere. The F and E regions of the ionosphere are shown. Note the weak ionization of the atmosphere even at high altitudes. (Picture based on Figure 1.6 in Ghosh, 2002.)](image)

The D layer is formed through penetration down to low altitude of energetic ionization sources. The principal source is the Lyman-α emission (121.6 nm), which ionizes mainly NO at 70-80 km. During high solar activity, 0.1-1nm X-rays become important, producing the molecular ions N$_2^+$ and O$_2^+$ at 80-90 km. Cosmic rays reach below 70 km and are responsible for the ionization at
these low altitudes. The E layer is centred at around 110 km and is composed mainly of $O_2^+$ and NO$^+$ produced by solar UV light (100-150 nm) and X-rays (1-10 nm). In the F layer, UV light in the range between 10 and 100 nm ionizes mainly atomic oxygen.

### 2.3.2.2 Ionospheric convection

In magnetized plasmas magnetic reconnection is an important mechanism, which merges magnetic field lines of opposite direction. As a result, stored electromagnetic energy is quickly transformed into kinetic and thermal energy of the plasma particles. During periods of southward interplanetary magnetic field (IMF), magnetic reconnection occurs at the subsolar point on the dayside magnetopause, and plasma is convected in the magnetosphere as depicted in Figure 2.6(a). This process moves the foot points of the magnetic field lines anti-sunward in the central polar cap and sunward at lower latitudes. Cold particles will follow the convection pattern of the magnetic foot points and as a result an electric field is built up in the polar caps:

$$ E = -v \times B = -\nabla \Phi. \quad (2.7) $$

$\Phi$ is referred to as the *cross-polar cap potential*. Equipotential contours of this potential are perpendicular to both the electric and magnetic fields, which means that the convection flow will be along these contours. In the polar cap proper the electric field is directed towards dusk, while it is directed towards dawn in the auroral region (see Figure 2.6(a)).

**Figure 2.6:** (a) During southward IMF, reconnection (red) on the dayside drags magnetic field lines tailward, until reconnection in the tail merges the field lines, which then return towards the Earth. (b) The foot points of the magnetic field lines create a convection pattern (red) in the high-latitude ionosphere. As a result, an electric field (blue) is built up. The convection pattern follows equipotential contours of the polar cap electric field.
The convection pattern has recently been mapped out by Haaland et al. (2007) using data from the Cluster satellites in the lobes. The measurements show that the convection pattern stagnates during northward IMF. They also show that the net drift differs slightly from the schematic pattern in Figure 2.6(b), due to a small rotation toward dusk on the nightside of the symmetry line of the potential contours. This asymmetry is transferred to the ion outflow pattern in the lobes, as has been shown in Paper V. Another important effect of the cross polar cap potential for the high-latitude low-energy ion outflow is that it governs centrifugal acceleration, which accelerates the ions along the diverging and curved magnetic field lines in the polar regions, and is an important acceleration mechanism for these outflows (Cladis, 1986; Horwitz et al., 1994; Nilsson et al., 2008).
Chapter 3

Escape of the atmosphere

The Earth’s atmosphere constantly loses matter through different processes. Here we will examine the two dominant types of escapes:

1. Escape of neutrals.
2. Plasma loss.

These atmospheric escape processes could also be grouped as thermal and non-thermal outflows. Thermal outflow refers to escape of neutrals due to the thermal motion of the atmospheric atoms or molecules. The theory was formulated by Jeans (1902), and is therefore named Jeans escape. This outflow is simply due to the thermal motion of the atmospheric atoms or molecules. To maintain the thermal outflow, there must exist continual energy sources. For the Earth and the other terrestrial planets, the supplied energy comes mainly from solar UV heating. Non-thermal outflow consists primarily of ion outflow along open magnetic field lines in the polar regions, as well as charge exchange mainly between atmospheric atoms and plasmaspheric protons. Since the plasmasphere is confined within closed magnetic field lines at lower latitudes and the ionospheric outflows occur at higher latitudes, the geographic regions of these two non-thermal processes are complimentary. In addition to these loss mechanisms, ions can escape through plasmasphere detachments. For the high-latitude ion outflow, we will emphasize the low-energy outflows, since those constitute the most important part of the ion outflow, and they are also the focus of this thesis.

A large difference between the neutral escape and the ion outflow, is that the neutral atoms are, in contrast to the ions, not confined in the Earth’s magnetic field and once they obtain sufficiently high energy they will be lost directly to space, unless they are ionized on their way out.
3.1 Escape of neutral atoms

In Jeans escape the thermal motion of the atoms and molecules allows them to escape the gravitational field of the Earth. The classical model postulates that collisions are frequent in the atmosphere below the exobase and that atoms and molecules can be represented by Maxwellian distributions, while the exosphere is fully collisionless\(^1\) (Jeans, 1925; Chamberlain, 1963). The thermal escape can thus be derived from the escape velocity at the exobase. The escape velocity is given by the balance between the gravitational potential energy and the kinetic energy of the escaping atom or molecule:

\[
v_{\text{esc}} = \sqrt{\frac{2GM_E}{r}}.
\]  

(3.1)

At the exobase \((r = r_e \sim 450 \text{ km})\) the escape velocity is 11 km/s. The corresponding escape energy for hydrogen is 0.61 eV, for helium 2.4 eV and for oxygen 9.7 eV. Particles with outward velocity in excess of the escape speed will be lost from the atmosphere and the Jeans escape flux is

\[
\Phi_J = \frac{n_{\text{exo}}}{2} \sqrt{\frac{2kT_{\text{exo}}}{m\pi}} (1 + \lambda_{\text{exo}}) e^{-\lambda_{\text{exo}}},
\]  

(3.2)

where \(n_{\text{exo}}\) and \(T_{\text{exo}}\) are the number density and temperature of the escaping species at the exobase (Shizgal and Arkos, 1996). The parameter \(\lambda_{\text{exo}}\) is defined by

\[
\lambda_{\text{exo}} = \frac{m v_{\text{esc}}^2}{2kT}.
\]  

(3.3)

Its physical significance can be understood if we use the expression for \(v_{\text{esc}}\) in Equation 3.1 and rewrite it on the form

\[
\lambda_{\text{exo}} = \frac{GM_E m / r_{\text{exo}}}{kT} = \frac{\text{gravitational potential energy}}{\text{random kinetic energy}}.
\]  

(3.4)

In the limit where \(\lambda_{\text{exo}} \to 0\), the random kinetic energy is so high compared to the potential energy that the atmosphere is no longer gravitationally bound. This is known as the Jeans limit and corresponds to the maximum thermal escape flux. On the other hand, for high values of \(\lambda_{\text{exo}}\), the atmosphere is effectively retained (Strobel, 2002).

\(^1\)In reality, the probability for an upward moving ion with speed over the escape velocity to escape without collisions is \(e^{-1}\) at the exobase (Strobel, 2002).
3.1. ESCAPE OF NEUTRAL ATOMS

The thermal escape flux from the atmosphere is obtained from the Jeans flux corrected by a factor $B$ (Fahr and Shizgal, 1983; Hunten, 2002):

$$\Phi_{\text{esc}} = B \Phi_J.$$ \hspace{1cm} (3.5)

$B$ is on the order of 0.5 and is introduced to account for the loss of fast particles close to the escape velocity, which makes the high-energy distribution far from Maxwellian and thus the actual escape rate is less than that predicted by Jeans (1925).

For typical conditions at the exobase, the theoretical estimate of the hydrogen flux is $5 \times 10^7$ cm$^{-2}$s$^{-1}$ (Hunten and Strobel, 1974) corresponding to a global outflow of $3 \times 10^{26}$ s$^{-1}$. The total outflow of He is on the order of $10^{18}$ s$^{-1}$, while the thermal outflow of O is completely negligible. As will be seen in Section 3.2, the outflow of He$^+$ is several orders of magnitude larger than the outflow of neutral He. Historically, this difference led to the postulation of the polar wind, since the neutral escape could not account for the total loss of helium from the Earth (Axford, 1968).

The main non-thermal escape mechanism involving neutrals is on the Earth the process of charge exchange. Typical charge exchange reactions involve plasmaspheric protons and atmospheric hydrogen or oxygen (Shizgal and Arkos, 1996):

$$\text{H}^+ + \text{H} \rightarrow \text{H}^* + \text{H}^+$$

$$\text{H}^+ + \text{O} \rightarrow \text{H}^* + \text{O}^+.$$ \hspace{1cm} (3.6)

The incoming hydrogen ions have typical temperatures up to 10,000 K, while the temperature of exospheric atoms is in the vicinity of 1,000 K. The resulting hydrogen atoms, H$^*$, thus possess significantly higher energy than the original atoms, and can escape at a higher rate than through thermal outflow. The global outflow of hydrogen due to charge exchange is on the same order as the outflow through Jeans escape and is then also around $3 \times 10^{26}$ s$^{-1}$. For helium the most efficient charge exchange reaction is that with molecular nitrogen followed by that with atomic oxygen. The total charge exchange loss of helium is on the order of $10^{23}$ s$^{-1}$ (Lie-Svendsen et al., 1992).

Charge exchange processes could also remove species with higher mass, such as oxygen, since they can obtain higher energies than the escape energy. However, in that case, the ions should exclusively originate in the high-latitude ionosphere and have escaped through plasma outflow processes along open magnetic field lines. Those outflows will be treated in the next section.

The neutral escape processes described here, as well as the plasma outflows, are dependent on the number density at the exobase, since they need supply of atoms from lower atmospheric regions. In the case, when the atoms are efficiently transported from below, the exobase density will not be a limiting
factor. However, if the supply is slow, the flux is limited by the flux at lower altitudes and dependent on the diffusive processes in these regions. The flux is then referred to as diffusion-limited (Hunten, 1973). On the Earth the flux is diffusion-limited and the density at the exobase is then adjusted so that the total escape, both from thermal and non-thermal processes, is constant. When the thermal escape rises, the non-thermal escape is thus reduced. During typical conditions the total flux on the Earth is limited to around $1.5 - 3 \times 10^8 \text{ cm}^{-2} \text{s}^{-1}$ (Yung et al., 1989; Shizgal and Arkos, 1996; Hunten, 2002).

### 3.2 Plasma loss

The outflows from the ionosphere can be divided into two types (Yau and André, 1997):

1. Bulk ion outflows.
2. Energization processes where only a fraction of the ions are energized.

Ion energization processes include for example ion conics and ion beams. In these processes often only a fraction of the ions participate in the outflow. This is in contrast to the bulk ion outflows, such as the polar wind and auroral bulk outflows, where the whole particle distribution is moving. Therefore the bulk outflows constitute the major part of the loss.

Bulk outflows occur at all latitudes, but it is only at high latitudes that they will directly escape to the outer magnetosphere. At low latitudes the outflows fill the plasmasphere, which is confined within closed magnetic field lines. Slightly higher up, in the lower part of the nightside auroral region, the field lines are directly connected to the plasma sheet and the outflowing ions fill this region. The plasma sheet ions originating in the ionosphere can later be lost from the magnetosphere by charge exchange on cold hydrogen atoms in the outer atmosphere (Moore and Horwitz, 2007), and the trapped plasmasphere ions can be released in plasmasphere detachments during geomagnetic storms.

Ion outflows in the polar caps and the parts of the auroral regions connected to open magnetic field lines fill the geomagnetic tail lobe. When moving farther down the tail the outflows from different sources are mixed, and they are normally difficult to distinguish from each other when measuring at high altitudes. In Papers IV and V we estimate the total outflow of low-energy H$^+$ from the polar regions, regardless of their source region or outflow mechanism. Since they originate in the polar ionosphere, we refer to them as high-latitude low-energy outflows. They include both the polar wind and upflows in the auroral region, but not plasmasphere detachments.
3.2. PLASMA LOSS

3.2.1 Polar wind
The polar wind, named after its similarities to the solar wind, was theoretically predicted by Axford (1968) and Banks and Holzer (1968) by arguing that the light ions in the ionosphere attain enough energy to escape the Earth’s gravitational field. The outflow is driven by the gradient in the electron pressure, which makes the electrons move upward. To maintain charge neutrality, an ambipolar electric field is built up and the ions are dragged upward along with the electrons. Thus, a larger outflow of electrons automatically gives rise to a larger outflow of ions. This is evident for example in the polar wind on field lines connecting to the sunlit ionosphere, where the outflows are significantly larger than on the nightside, due to escaping photoenergized atmospheric electrons (Yau and André, 1997; Moore et al., 1999a). Also, if the plasma electrons are heated, energy is transferred to the total system and enhance the escape from the system.

3.2.2 Auroral bulk outflows
The overall process of ion outflows normally occur in several sequences, especially for the heavier ions, such as O$^+$ that need more energy. At low altitudes the constituents can get energized by principally two processes: (1) Heating of ions by frictional collisions in the topside F-layer, and (2) Electron heating by impact of precipitating auroral electrons (Wahlund et al., 1992; Moore and Horwitz, 2007). The first mechanism is important for all ionospheric outflows, whereas the second one only is active in the auroral region. These low-altitude processes will lead to enhanced outflow of light ions in the auroral region. The light ions will be additionally accelerated as a result of parallel electric fields and particle-wave interactions (Moore et al., 1999a). The combined effect of these energization mechanisms allows also heavy ions to escape from the ionosphere and the outflow contains a significant, if not dominant, fraction of O$^+$ (Yau and André, 1997; Moore et al., 1999a). Other heavy ions and molecular ions, such as N$^+$, NO$^+$, N$_2^+$, O$_2^+$, can at times be present in observations, but are rare due to lower ionospheric densities (see Figure 2.5) and high escape energies. Depending on the solar wind and geomagnetic conditions, the heavy ion flux from the auroral region range from very small up to an order of magnitude higher than the total polar wind flux (Moore and Horwitz, 2007).

The upflowing ions originating in the dayside auroral regions, the cleft, will be transported tailward by antisunward convection. This combined motion of upflow and convection forms the cleft ion fountain (Lockwood et al., 1985). The O$^+$ content above the polar cap derive principally from the cleft ion fountain, since only a negligible fraction of heavy ions can escape through the polar wind.
3.2.3 Plasmasphere detachments

The plasmasphere is directly connected to the ionosphere and is thus filled with cold, dense plasma. At plasmasphere detachments, a part of the plasmasphere is ripped away and cold plasma is lost to the magnetosphere.

Cold dense plasma is at times observed in the dayside outer magnetosphere and at geosynchronous orbits. This plasma is released from the corotating plasmasphere during high geomagnetic activity and convected sunward and westward toward the magnetopause (see Figure 3.1), forming the detached plasmasphere (or plasmaspheric tail). The detachment occurs in connection to increases of the dawn-to-dusk convection electric field in the magnetosphere, which together with the corotation electric field confines the plasma in the plasmasphere (Matsui et al., 1999).

Figure 3.1: Schematic picture of a plasmaspheric detachment. (After Matsui et al., 1999.)
Chapter 4

Terrestrial matter balance

We have seen that the Earth can lose large amounts of matter from the atmosphere through thermal and non-thermal processes. However, the Earth can also accrete matter, mainly in the form of interplanetary bodies that cross the Earth’s orbit. In this Chapter, we quantify the total loss and accretion through different processes and examine whether the contemporary Earth in total loses or accretes matter.

The atmosphere itself can be supplied by compounds from e.g. volcanism, evaporation of oceans and combustion of fossil fuels, but can also lose matter through condensation and sequestration into the hydro- and lithospheres. Here we will regard the Earth and its atmosphere as one system, and thus only take processes that remove or supply matter to the whole system into account.

4.1 Quantifying the loss

In Chapter 3 we examined the different escape processes from the atmosphere through neutral escape and plasma loss. The neutral escape is due to thermal outflow and charge exchange and those two processes are approximately of equal importance. In Section 3.1 we estimated that each of these loss processes allows hydrogen atoms to escape at a rate of $3 \times 10^{26} \text{ s}^{-1}$. The loss of helium is several orders of magnitudes lower, while the oxygen escape is completely negligible.

The outflow of protons from the auroral zone and the polar cap is on the order of $10^{26} \text{ ions/s}$ (Papers IV, V; Cully et al., 2003a; Huddleston et al., 2005), while the He$^+$ outflow is considerably lower at around $10^{24} \text{ ions/s}$ (Su et al., 1998; Peterson et al., 2008). The O$^+$ outflow originates as mentioned predominantly in the auroral zone. The total outflow from high latitudes over all energies is around $0.7 \times 10^{26} \text{ ions/s}$ (Yau et al., 1988). Plasmasphere detachments release most matter during the first few hours after their creation ($2 \times 10^{26} \text{ ions/s}$) (Borovsky and Denton, 2008). During a complete geomag-
Table 4.1: Summary of different loss processes from the Earth’s atmosphere and ionosphere. The total loss is 3 kg s⁻¹ or around 100,000 tons/year.

<table>
<thead>
<tr>
<th></th>
<th>( \text{H/H}^+ )</th>
<th>( \text{He/He}^+ )</th>
<th>( \text{O/O}^+ )</th>
<th>Resulting mass flux (kg s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Neutral escape</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal escape</td>
<td>( 3 \times 10^{26} )</td>
<td>( 10^{18} )</td>
<td>-</td>
<td>0.5</td>
</tr>
<tr>
<td>Charge exchange</td>
<td>( 3 \times 10^{26} )</td>
<td>( 10^{23} )</td>
<td>-</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Plasma loss</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High-latitude</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>outflows</td>
<td>( 1 \times 10^{26} )</td>
<td>( 10^{24} )</td>
<td>( 7 \times 10^{25} )</td>
<td>2</td>
</tr>
<tr>
<td>Plasmasphere</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>detachments</td>
<td>( 0.3 \times 10^{26} )</td>
<td>( 0.8 \times 10^{25} )</td>
<td>( 0.4 \times 10^{25} )</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Sum</strong></td>
<td>( 7.3 \times 10^{26} )</td>
<td>( 10^{25} )</td>
<td>( 7.4 \times 10^{25} )</td>
<td>-</td>
</tr>
<tr>
<td><strong>Sum (kg s⁻¹)</strong></td>
<td><strong>1.2</strong></td>
<td><strong>0.06</strong></td>
<td><strong>1.9</strong></td>
<td><strong>3.2</strong></td>
</tr>
</tbody>
</table>

4.2 Accretion processes

The most important accretion process to the Earth and its atmosphere is accretion through meteoritic material. In a typical year the mass flux to the Earth is dominated by particles below 1 mm in size (Love and Brownlee, 1993), while on the longer time scales (over 1000 years) larger bodies over a million tons
Interplanetary matter | Mass range (kg) | Accretion (kg s\(^{-1}\))
---|---|---
IDP and Micrometeorites\(^a\) | \(10^{-12}–10^{-7}\) | 1.3
Meteorites\(^b\) | \(10^{-6}–10^{5}\) | 0.06
Airbursts\(^c\) | \(10^{-3}–10^{-9}\) | 0.3
Big impacts\(^d\) | \(>10^{5}\) | 4.4
**Sum (without big impacts)** | | **6.1**
**Sum (total)** | | **1.7**

Table 4.2: Summary of accretion of interplanetary matter. The largest influx is from big impacts of large bodies over hundreds of thousands of tons in mass, but those impacts occur very rarely. During a typical year the submillimeter particles instead dominate and the mass flux is then around 2 kg/s. [\(^a\)Love and Brownlee (1993), \(^b\)Kyte and Wasson (1986), \(^c\)Chyba (1993); Chyba and Hand (2006), \(^d\)Ceplecha (1992)].

tend to dominate (Ceplecha, 1992). Table 4.2 summarises the yearly accretion of interplanetary matter.

Interplanetary dust particles (IDP) constitute a major source of mass accretion to the Earth. Love and Brownlee (1993) estimated that IDP and micrometeorites in the mass range \(10^{-12}–10^{-7}\) kg (6-300 μm for 1 g/cm\(^3\) particles) supply the Earth by around 1.3 kg/s. The mass flux peaks for particles with mass around \(1.5 \times 10^{-8}\) kg.

Over longer periods, interstellar dust could contribute in small amounts to the Earth’s mass, whenever the Solar System passes through clouds of interstellar dust. However, these passages are very rare, and the accretion is negligible compared to the contribution from other sources (Chyba and Hand, 2006).

Meteorites in the mass range \(10^{-6}–10^{5}\) kg are estimated to supply around 2,000 tons per year to the Earth (Figure 4 in Kyte and Wasson, 1986). Bodies with size 1-100 m (\(10^{3}–10^{9}\) kg), including comets and asteroids, may explode in the Earth’s atmosphere in catastrophic airbursts. The contribution from airbursts due to explosion of bodies in this size range is around 0.3 kg/s (Chyba, 1993; Chyba and Hand, 2006).

While bodies up to a few meters are small enough to be significantly decelerated in the Earth’s atmosphere and completely destroyed in an airburst, larger bodies are likely to pass through the atmosphere and impact the surface at very high velocities. Such big impacts dominate the mass influx to the Earth with around 4.4 kg/s (Ceplecha, 1992) . However, they occur very infrequently. Bodies above \(1 \times 10^{12}\) kg account for more than 90% of the total mass flux of the big impacts, but the time between two such events is over 100,000 years.
During typical conditions, the accretion of interplanetary matter is therefore around 2 kg/s or 60,000 tons/year. The incoming interplanetary matter could have played an important role for the formation of life on the Earth. Chyba and Hand (2006) reviewed the amount of prebiotic organic molecules supplied from extra-terrestrial sources for different types of model atmospheres of the early Earth. IDPs are believed to contribute most organic matter, while shocks from impacts and airbursts could have started chemical reactions forming organic compounds in the atmosphere.

Figure 4.1: Sketch of the terrestrial matter balance. Red arrows correspond to thermal outflow, which occurs at all latitudes. Green arrows display plasma outflows. At low latitudes they fill the plasmasphere, while at high latitudes the outflowing ions are allowed to escape into the magnetotail lobes. Other loss processes are charge exchange (blue) and plasmasphere detachments (purple). The Earth accretes matter through influx of interplanetary bodies. On short time scales (less than thousands of years), small objects below 1 mm dominate the mass influx (orange). Big impacts of asteroids or comets (brown) contribute in large amounts, but they occur very rarely. The accretion and loss are on the same order of magnitude.

4.3 Total balance
The accretion and loss processes to the Earth-atmosphere system summarized in the previous sections will show large variations with season, solar and magnetic activity, as well as with fluctuations in the interplanetary body content in the Solar System. However, during a typical year, the loss and accretion pro-
cesses are comparable. On longer time scales the Earth-atmosphere system will accumulate mass, since big impacts become important. In Figure 4.1 the different accretion and loss processes are shown.

The total mass of the Earth’s atmosphere is $5 \times 10^{18}$ kg (Wayne, 1991), which means that even if there were no supply mechanisms from neither interplanetary impacts nor the litho- and hydrospheres, the yearly atmospheric loss of around 100,000 tons is vanishingly small. Oxygen escape accounts for the largest mass loss, while hydrogen is lost in largest amounts. The escaping hydrogen atoms originate mainly in the oceans, releasing oxygen into the atmosphere. Over the past billion years this reaction has caused the sea level to decline by a couple of meters globally (Hanslmeier, 2007).
Chapter 5

Ionospheric matter in the magnetosphere

As has already been mentioned, outflows from the ionosphere constitute a significant source of plasma supply to the magnetosphere. The outflowing low-energy ions from the polar caps continue out in the magnetospheric tail lobes without being significantly energized and fill large regions of the magnetosphere with cold plasma.

In spite of its abundance in the magnetosphere, few measurements of the cold plasma have been possible to make. Even though numerous simulations have shown that the ionospheric outflows fill the magnetotail lobe, the lack of large surveys in these regions has created an uncertainty of the importance of cold ionospheric ions in the magnetosphere. Papers IV and V address this, showing that cold ions are almost omnipresent in the lobes. To put these two studies into context, a short review of previous important observations of ions with very low energies (thermal energy on the order of 10 eV) is given here. We also discuss different controlling factors for plasma outflows and the final fate of the outflowing ionospheric ions.

5.1 Observations of cold plasmas in the magnetosphere

Observations of cold space plasmas with energies on the order of a few eV are problematic. The difficulties occur especially in low-density regions, where the spacecraft potential can reach several tens of volts (see Section 6.2.1). Low-energy ions will be shielded out by the potential barrier and will never be able to reach any ion detector mounted on the spacecraft.

In this section, we will investigate some important observations, where the geophysical setting or the spacecraft setup has allowed detection of cold plasmas in different regions of the magnetosphere. Figure 5.1 summarises where
these observations have been carried out. References to other investigations of cold ions can be found in the introductory paragraphs of Papers III-V.

**Figure 5.1:** Schematic view of the magnetosphere and regions, where important observations of low-energy ions have been made. (1) Studies of outflowing ions in the polar caps (see references in text). (2) High-altitude polar wind studied by Su et al. (1998) and Moore et al. (1997). (3)-(5) Cold plasma in the plasma sheet and the plasma sheet boundary layer (PSBL) observed by Etcheto and Saint-Marc (1985), Seki et al. (2003) and Sauvaud et al. (2004). (6) Our studies of the high-latitude low-energy ion outflow in the lobes (Papers III-V). These studies cover a large volume in regions of the magnetosphere where the outflowing ions previously have been invisible. (7) Example of one of the event observations of cold dense ion flows observed by Geotail far back in the magnetotail (Mukai et al., 1994; Hirahara et al., 1996). (8)-(9) Studies of cold plasma populations in the dayside magnetosphere by Chen and Moore (2004) and Sauvaud et al. (2001).

### 5.1.1 Polar regions

Recent observations of the polar wind have been reviewed by Yau et al. (2007), while Moore and Horwitz (2007) have covered ablation of the atmosphere with emphasis on outflows in the auroral region. Here we give a brief overview of observations of low-energy ion outflows from the polar regions and focus on the high-altitude measurements by Su et al. (1998), since those are the most appropriate to compare our results to.
The first direct measurements of the outflows in the polar region was achieved in the late 1960’s by Explorer 31, which found \( \text{H}^+ \) outflows at 500 and 3000 km with velocities up to 15 km/s (Hoffman, 1970). ISIS 2 confirmed the outflow of \( \text{H}^+ \), and also found evidence for outflows of \( \text{He}^+ \) and \( \text{O}^+ \). Oxygen was shown to be the dominant ion species at the satellite altitude (1400 km) during magnetically quiet times (Hoffman et al., 1974; Hoffman and Dodson, 1980). The measurements from both Explorer 31 and ISIS 2 were carried out at low altitude, where the densities were high and thus the spacecraft potentials low. Contributions to the understanding of the polar outflows have also been made by DE-1 (Nagai et al., 1984; Yau et al., 1988). The current knowledge of these outflows can mainly be attributed to studies by Akebono (Abe et al., 1993, 1996, 2004; Cully et al., 2003a) and Polar (Su et al., 1998; Moore et al., 1997; Chappell et al., 2000; Huddleston et al., 2005).

In Papers III-V we have studied ionospheric outflows at large geocentric distances (5-19 \( R_E \)). Previous studies at high altitudes have been rare because of high positive spacecraft potentials. The study at highest altitude was conducted by Su et al. (1998), who used Polar data to investigate the polar wind at two different altitudes: 8 \( R_E \) (apogee, northern hemisphere) and 5000 km (perigee, southern hemisphere). Polar carries the ion detector TIDE (Thermal Ion Dynamics Experiment), which operates with good resolution in the 0.3-450 eV energy range. Together with the Plasma Source Instrument (PSI), which reduces the spacecraft potential to approximately +2 V by creating a plasma cloud around the spacecraft, TIDE is able to measure low-energy ions up to high altitudes (Moore et al., 1997).

Figure 5.2 illustrates the observed characteristics of the high altitude polar wind. These polar wind observations suggest a faster, hotter and more rich in \( \text{O}^+ \) plasma than predicted by thermal outflow theories. The discrepancy between theory and observations was interpreted as a result of neglecting energy input in the topside auroral ionosphere (Moore et al., 1999a). At 5000 km, the \( \text{H}^+ \) are outflowing, but the mean velocity of \( \text{O}^+ \) is directed downward (see Figure 5.3). The high altitude \( \text{O}^+ \) ions can thus not originate from the polar cap proper, but are transported into the polar cap from the dayside auroral zone by the cleft ion fountain. Parts of the oxygen distribution are again trapped in the Earth’s gravity field over the polar caps and flow downward.

The polar wind survey by Su et al. (1998) arrived at the following parameters of the polar wind:

**Density** At 5000 km the dominant ion species is \( \text{O}^+ \) \( (n_{\text{O}^+} \approx 8 \text{ cm}^{-3}, n_{\text{H}^+} \approx 2 \text{ cm}^{-3}) \), whereas at 8 \( R_E \) the plasma is totally dominated by \( \text{H}^+ \) \( (n_{\text{O}^+} \approx 0.05 \text{ cm}^{-3}, n_{\text{H}^+} \approx 0.3 \text{ cm}^{-3}) \). \( \text{He}^+ \) only constitutes a small fraction of the total number of ions at both altitudes.
Figure 5.2: Observations of the high altitude polar wind, for H\(^+\) (upper panels) and O\(^+\) (lower panels). (After Su et al., 1998.)
Flow speeds The polar wind flow speeds show large variations with altitude:

- **5000 km**: The H\(^+\) ions are supersonic and upflowing with an average speed of 15 km/s, while the O\(^+\) ions are subsonic and moving towards the earth with an average speed of 1 km/s.
- **8 \( R_E \)**: Both H\(^+\) and O\(^+\) are supersonic and flowing upwards. The average speed for H\(^+\) is 45 km/s and for O\(^+\) 27 km/s.

The results for outflowing protons of *Su et al.* (1998) at low altitudes have later been adjusted using revised spacecraft potential measurements (*Scudder et al.*, 2000). This correction gives just a slight increase in the proton velocity, whereas the density increases by a factor of 3 and the outward flux can increase by as much as a factor of 5 (*Huddleston et al.*, 2005). The revised flux is consistent with theoretical predictions (*e.g.* *Schunk and Sojka*, 1997) as well as other observations (*Paper IV* and references therein).

*Su et al.* (1998) admit that the results at 8 \( R_E \) are somewhat in contradiction with polar wind models. We suggest that the discrepancy between theory and observations to some extent could be explained by the fact that the lowest detectable flow speed for cold hydrogen ions with Polar is 20 km/s. This speed corresponds to a flow energy of 2 eV, which is the energy the ions need to surmount the remaining potential barrier of the spacecraft at 2 V. If many ions have flow speeds below 20 km/s, which is expected from outflow theories and observations at lower altitudes, and also confirmed in our observations at large geocentric distances (*Papers IV, V*), the statistics in panel 2 (first column, second row) in Figure 5.2 will show only the tail of the distribution. This is supported by Figure 5.4, where the velocity distributions from the *Su et al.* (1998) study and our study (*Paper V*) are combined. The tail of the distributions are very similar, but at low velocities there are large differences. In particular,
our velocity peak is located close to the detectable limit of the Polar study at around 20 km/s. As a result our mean velocity is considerably lower. It should be noted that we also might miss some of the ions with the very lowest velocities, since our method relies on ion drift speeds higher than the ion temperature (see Section 2.3 of Paper V).

The spacecraft potential screening effect is not a problem for O\(^+\) ions with the same speed, since they are much heavier. At 5000 km a large portion of the hydrogen ions are shielded as well, but these data have been corrected for the spacecraft potential (\(\geq 1.8\) V) using a bi-Maxwellian filling in procedure, explaining why it is possible to attain low average velocities for H\(^+\) (Su et al., 1998).

Figure 5.4: Comparison between the velocity distributions of low-energy ions from the Su et al. (1998) study (white) and from our study presented in Paper V (green). Our data have first been normalized to the highest occurrence rate of Su et al. (1998) and then shifted half a bin to the right to improve readability.

**Temperature** At 5000 km the perpendicular temperatures are higher than the parallel temperatures for both ion species, which may indicate perpendicular heating by wave-particle interactions. At 8 \(R_E\) the parallel temperatures are higher than the perpendicular temperature, probably as a result of adiabatic conversion of perpendicular to parallel energy during outward motion along magnetic field lines. The temperature of O\(^+\) is higher than of H\(^+\) at both altitudes.
5.1 OBSERVATIONS OF COLD PLASMA

5.1.2 Magnetotail

Cold ions originating in the ionosphere have been observed in the lobes, the plasma sheet boundary layer (PSBL) and the plasma sheet. Seki et al. (2003) reported cold ions in the plasma sheet, which were exempted from heating. The observations were made by the Geotail spacecraft at positions from 8 to 27 \( R_E \) behind the Earth. At the time of observation the spacecraft was in eclipse behind the Earth, yielding a negative spacecraft potential as a result of inhibited photoelectron emission. The negative spacecraft potential allowed detection of all distributions of ions, regardless of temperature. The authors suggest that the cold ions may not have passed through the boundary heating region adjacent to the plasmasheet (the PSBL), but have directly flown out from the ionosphere.

Similar measurements were made more than 20 years earlier at lower altitudes (around 6 \( R_E \)) with the two geosynchronous satellites Applied Technology Satellite 6 and SCATHA (Olsen, 1982). When the spacecraft were in eclipse, an isotropic cold ion population (\( T_i \approx 1 \text{eV} \)) was measured close to the inner edge of the plasma sheet at local midnight. This hidden population was only found at quiet times (\( K_p \leq 2 \)) and when the magnetic activity had been low for several hours before, which showed to be in only a few percent of the eclipse events.

In the PSBL Etcheto and Saint-Marc (1985) found "anomalously" high plasma densities (around 5 cm\(^{-3}\)) and low perpendicular energies (less than 30 eV) using measurements from a relaxation sounder on board the two ISEE spacecraft. The cold and dense plasma was believed to originate in the ionosphere, and then transported to the PSBL through plasmasphere detachments or high-latitude ion outflows.

Sauvaud et al. (2004) have presented case studies of cold ions in the lobes, the plasma sheet and PSBL using the Cluster ion spectrometers (CIS). These ions have only been detected for high drift velocities, when the drift energy is high enough to overcome the spacecraft potential barrier. The study confirms the idea of transport of ionospheric ions into the magnetotail and show in particular that ions are massively injected from the nightside ionosphere into the tail during storms and substorms. One single injection event can even account for over 80% of the plasma sheet \( O^+ \) population. Furthermore, the observations of a cold proton population inside the PSBL during quiet times preceding a substorm was reported. The cold ions are accelerated to several hundreds km/s, which allows precise density measurements of this population. The density of the cold population of around 0.1 cm\(^{-3}\) is almost comparable to the density of the hot plasma sheet ions, which reaches a maximum of 0.25 cm\(^{-3}\) in this study. Other examples, where accelerated cold ions in the magnetotail have been able to overcome the spacecraft potential barrier, have been seen by the ISEE spacecraft (Orsini et al., 1990) and Geotail (Mukai et al., 1994; Hirahara et al., 1996; Seki et al., 1998).
5.1.3 Dayside magnetosphere

Plasmaspheric detachments can expel large amounts of cold dense plasma into the dayside magnetosphere. This has been observed by many spacecraft from the early years of space exploration till today (Chen and Moore, 2004, and references therein). Observations from the IMAGE mission in combination with simulations have shed new light on the mechanism and evolution of the plasmaspheric drainage plumes (Goldstein et al., 2002, 2003). A statistical study of hundreds of plume crossings was conducted by Borovsky and Denton (2008), making it possible to estimate the amount of plasma expelled in an average detachment (see Section 4.1).

The plasmaspheric plasma expelled through detachments contributes to both microscale and macroscale physical processes in the dayside magnetosphere. Observations by Polar (Chen and Moore, 2004) have revealed a large number of plasmaspheric ions flowing with high velocity towards the subsolar magnetopause. These fast flows seem to occur predominantly at southward IMF, which may suggest that they are related to the process of reconnection at the dayside magnetopause: the plasmaspheric detachment flows to fill the low density reconnection region, bringing its frozen in flux tubes towards the approaching solar wind, thus contributing to new reconnection processes.

Cold ions have also been observed by Cluster in the upper dayside magnetosphere adjacent to the magnetopause (Sauvaud et al., 2001). These ions became visible to the ion instrument only when they were accelerated by intermittent motion of the magnetosphere. However, they were shown to exist all the time by simultaneous observations of the total plasma density with the relaxation sounder WHISPER (Décréau et al., 2001). The density of this cold ion population was found to be as high as 1 cm$^{-3}$, which is much higher than the surrounding local density of ions.

5.2 Factors controlling plasma outflows

In the simple picture plasmasphere detachments occur mainly during geomagnetic storms, when increased convection results in erosion of the outer part of the plasmasphere. More detailed information on driving mechanisms behind the formation of plasmaspheric drainage plumes can be found in the papers by Matsui et al. (1999) and Borovsky and Denton (2006, 2008). Here we will focus on the factors controlling the high-latitude low-energy outflow.

Before examining the different mechanisms in detail, we should note that the outflow properties are dependent on the altitude of the energy input that drives the outflow. The theory of stellar winds states that if energy is added in the subsonic region the outward mass flux will increase, whereas if it is added in the supersonic region it is instead the outward velocity that increases (Leer and Holzer, 1980). The same pattern is anticipated to appear in the
ionospheric outflows with energy added at low altitudes increasing the mass flux and energy added higher up increasing the outflow velocity (Moore and Horwitz, 2007).

The polar wind is mainly varying with solar UV flux, since it controls the ionization rate and photoelectron production in the ionosphere. Therefore the polar wind is sometimes referred to as photothermal outflow (Moore and Horwitz, 2007). The auroral outflows, on the other hand, are enhanced during active times, when the solar wind-ionospheric coupling is strong. Since the solar wind energy input shows larger variability than the solar radiation, the auroral wind is much more variable than the polar wind. Nsumei et al. (2008) have shown that solar illumination controls the plasma density over the polar caps mainly at low altitudes (below 2.5 RE), whereas it is controlled by the geomagnetic activity at higher altitudes (above 4 RE). The dependence on geomagnetic activity is explained by the fact that at high altitudes the plasma originates from other regions than the polar cap proper: the cleft ion fountain and possibly also plasmaspheric plumes supply plasma to the polar cap during active times. As was shown by Lockwood et al. (1985), the convection during active times is strong enough to fill the entire polar cap with ions from the cleft ion fountain. During quiet times these ions are instead to a large extent restricted to the dayside region.

In ionospheric outflow studies, the F10.7 index is often used as a measure of the solar UV flux producing photoionization in the Earth’s ionosphere. The outflow flux is strongly dependent on the F10.7 index, as has been shown in numerous studies (e.g. Yau et al., 1988; Cully et al., 2003a; Paper V). The outflow velocity seems to be little altered by the F10.7 level (Abe et al., 2004; Paper V), which indicates that the increased flux for high F10.7 mainly is due to the enhanced ion density and elevated photoelectron production. This is consistent with the theory of stellar winds cited above, as UV ionization and heating predominantly affects lower altitudes.

The outflow velocity and flux show clear seasonal variations, with higher velocities during local summer than during local winter (Abe et al., 2004; Lennartsson et al., 2004). However, Peterson et al. (2006) note that solar UV flux and geomagnetic energy input are more important than seasonal variations, which occur on longer time-scales. For the photothermal outflow, there is a clear day-to-night asymmetry with higher fluxes on the dayside (Abe et al., 1993; Nsumei et al., 2008). The region where the photothermal outflow occurs extends to lower latitudes during magnetically active times, since the auroral oval is expanded equatorward (Abe et al., 2004).

In many studies the dependence of the high-latitude ion outflow on the geomagnetic index $K_p$ has been investigated. In Paper V we compare the $K_p$ dependence of the global outflow as measured by Akebono (Cully et al., 2003a), by DE-1 (Yau et al., 1988), and by us on Cluster. For all three studies, the outflow increases roughly exponentially with $K_p$. However, since $K_p$ is a quasilogarithmic measure of magnetic activity, this suggests a quasi-linear depend-
ence of the outflow on magnetic disturbance (Yau and André, 1997). Abe et al. (1996) made a distinction between outflows from the polar cap proper and from the auroral region. They found no correlation with $K_p$ in the polar cap, but at auroral latitudes the dependence was strong.

In addition to solar radiation and geomagnetic activity, the bulk ion outflows are strongly dependent on the solar wind properties and the interplanetary magnetic field. The solar wind dynamic pressure has been identified as the main driver for plasma outflows (Moore et al., 1999b; Cully et al., 2003a; Lennartsson et al., 2004; Paper V). The dynamic pressure affects the energy and momentum input to the polar ionosphere and the effect is strongest in the dayside auroral zone, where the interaction is more direct (Moore and Horwitz, 2007).

The direction and magnitude of the interplanetary magnetic field are also strong drivers for the ion outflows (Cully et al., 2003a; Lennartsson et al., 2004; Paper V). The direction of the IMF affects the ionospheric convection pattern and thus the transport of ions. As a result, ion outflows are larger during periods of southward IMF.

## 5.3 Fate of ionospheric outflow

An interesting question is the final destiny of the outflowing ionospheric ions. If the ions would have stayed on the magnetic field lines in the lobes, they would all have been lost from the magnetosphere directly to the downstream solar wind. However, the ions will join the general convection pattern in the magnetosphere, and a majority will end up in the plasma sheet. This has been shown by both observations (Olsen, 1982; Orsini et al., 1990; Seki et al., 2003; Sauvaud et al., 2004) and computer simulations (Delcourt et al., 1994; Baker and Pulkkinen, 1998; Chappell et al., 2000; Cully et al., 2003b; Moore et al., 2005; Huddleston et al., 2005). But there is also a significant portion of the ions that have sufficient parallel velocity to escape directly to the downstream solar wind. Using Polar TIDE/PSI observations in combination with particle trajectory codes Chappell et al. (2000) and Huddleston et al. (2005) have shown that typical low-energy polar wind ions (less than 10 eV) travel out through the lobes into the magnetotail to supply the plasma sheet (see Figure 5.5). Moving into the plasma sheet the ions get heated fast to typical plasma sheet energies. Huddleston et al. (2005) computed realistic densities in the tail lobes, which are close to our measured values of the density of the cold ions in the lobes (Papers IV, V).

The global simulations by Cully et al. (2003b) with Akebono data as boundary conditions in the polar caps showed that the region, where substorms originate, is predominantly supplied by ionospheric plasma. Moore et al. (2005) included solar wind entry, as well as ion outflow, in a global simulation model. This study confirmed that the high-latitude ion outflows can dominate over
5.3. FATE OF IONOSPHERIC OUTFLOW

Figure 5.5: The high-latitude low-energy outflows supply plasma to the magnetosphere. The low-energy ions have previously been invisible to spacecraft in the lobes, due to spacecraft potential screening effects. In the simulations by Chappell et al. (2000) two thirds of the ions will convect into the plasma sheet, where they get energized. (After Chappell et al., 1987.)

the solar wind plasma in the near-Earth magnetosphere. The region, in which terrestrial plasma dominates, is often referred to as geospace.

The final destiny of the outflowing ions is mainly determined by three factors:

1. Field aligned velocity.
2. Magnetospheric convection.
3. Source region of the ions.

The field aligned velocity of outflowing ions is strongly dynamic and depends on many different parameters, as described in the previous section. One such parameter is the sign of the $Z$ component of the IMF, which is also important for magnetospheric convection. Figure 5.6 shows the influence of the sign of IMF $B_Z$ on the final destiny of outflowing ions. For southward IMF ($IMF\ B_Z < 0$), dayside reconnection creates a strong magnetospheric convection first tailward, and then towards the central plasma sheet. The plasma will follow the convection pattern shown in Figure 2.6(a). The anti-sunward convection in the polar caps will create enhanced outflow fluxes in the magnetotail lobes. As has been seen in many simulations, the strong cross-tail electric field will lead to convection towards the central tail and a majority of the ions will reach the plasma sheet before the X line, where tail reconnection occurs. The plasma sheet ions thus originate predominantly in the ionosphere during southward IMF. Only the ions reaching the central tail beyond the X line will directly be lost to the downstream solar wind.

When the IMF turns northward ($IMF\ B_Z > 0$), reconnection instead occurs at high latitudes. This opens up the magnetopause for direct entry of solar wind plasma at high latitudes. This enhanced solar wind entry compresses geospace. The outflows in the lobes are weaker during northward IMF, since
CHAPTER 5. IONOSPHERIC MATTER

Figure 5.6: The fate of ionospheric outflows is mainly determined by the sign of the $Z$ component of the interplanetary magnetic field, IMF. (a) Southward IMF leads to dayside reconnection (red) close to the subsolar point. Ionospheric convection is strong and follows the pattern shown in Figure 2.6(b), which leads to enhanced tailward outflows. The cross-tail electric field and current are also intense, leading to fast tail lobe convection towards the plasma sheet. During southward IMF the plasma sheet is mainly filled by ionospheric plasma, which will get heated quickly once it has entered into the plasma sheet. (b) During northward IMF reconnection occurs at high latitudes. This will lead to enhanced solar wind entry in this region. As a result, geospace – the region which is dominated by plasma of terrestrial origin – is compressed. Ionospheric convection has stagnated or could even turn sunward, leading to weak fluxes of ionospheric ions in the tail lobes. At the same time, the convection in the lobes is slow, due to weak cross-tail electric fields. Therefore, a larger fraction of the outflowing ions will escape to the downstream solar wind and less ions reach the plasma sheet. The cold dense plasma sheet during northward IMF is supplied with plasma from the low-latitude boundary layer.
ionospheric convection stagnates (Haaland et al., 2007) or could even turn sunward (Moore et al., 1999a). At the same time, the ions will reach farther down the tail, since the convection towards the plasma sheet is weaker. In cases when the convection is very slow or even reversed, the outflowing ions will be lost through the lobes to the downstream solar wind or escape through the low-latitude boundary layer and magnetosheath. During northward IMF the plasma sheet becomes cold and dense, and is supplied with plasma of solar wind origin from the low-latitude boundary layer (Moore et al., 1999a).

Figure 5.7: In the centre of the figure a cross-section of the tail can be found. This schematic drawing from Gosling et al. (1985) illustrates the local entry of plasma through the magnetopause due to reconnection over the entire dayside magnetopause during positive IMF $B_Y$. Plasma convection will be faster on those sides of the lobes where most of the flux is entering. This can be seen in simulation results from Baker and Pulkkinen (1998) (top and bottom panels) using two different cross-tail electric fields (0.1 and 0.75 mV/m) for the different regions. Weak curves represent magnetic field lines, and bold curves represent stream lines. (After Baker and Pulkkinen, 1998.)

Another important factor for the fate of the ions, is the direction of IMF $B_Y$ in combination with the source region. As, can be seen in Figure 5.7, the cross-tail electric field does not necessarily have to be uniformly distributed over the tail cross-section. The magnetopause can be locally open in opposite quadrants in the northern and southern hemispheres, due to the influence of IMF $B_Y$ on dayside reconnection. For positive (negative) IMF $B_Y$ the magne-
topause is locally open in the northern dawn (dusk) boundary and southern dusk (dawn) boundary. In regions, where the magnetopause is locally open, convection toward the central tail will be stronger than in locally closed regions. Therefore, it is possible to get weak convection in large regions of the lobe even during southward IMF, which will allow ions to travel far away from the Earth before convecting to the tail centre (Baker and Pulkkinen, 1998). A larger portion of the ions could then possibly be lost directly from the magnetosphere than has been found in typical simulations not taking this effect into account.

Even those ions that will not escape directly from the magnetosphere, but convect into the plasma sheet, will ultimately be lost through charge exchange with neutral exospheric atoms (Moore and Horwitz, 2007). As depicted in Figure 5.5, the cold ions entering the plasma sheet will get heated and transported towards the Earth. Results from the IMAGE satellite have shown that energetic auroral outflows entering the plasma sheet will be lost from the magnetosphere through charge exchange (Moore and Horwitz, 2007). This process should apply even if the ion energy stays low, since the cross-section for the charge exchange reaction between an ion and an exospheric atom is large also for low energies (Paper IV). Therefore, the large majority of ions participating in ionospheric outflows will eventually be lost from the magnetosphere.
Chapter 6

A new measurement technique for cold plasma flows

In this chapter we present the entirely new measurement technique we have used to study cold flowing plasma. The technique is based on the detection by electric field instruments of the large electrostatic wake created behind a spacecraft in such an environment. To get a background, we will first explain the theory behind probe measurements of electric fields, then investigate important spacecraft-plasma interactions and wake effects in the Cluster data. Finally, we briefly explain the method for detecting and measuring the flux of cold flowing plasmas.

6.1 Probe measurements of plasma

Many plasma instruments designed for measurements of electric fields, density and temperature are based on the Langmuir probe theory, which for low densities (probe much smaller than the Debye length) was developed by Mott-Smith and Langmuir (1926). These instruments use probes collecting particles from the ambient plasma. To understand the functioning of the probe instruments, it is essential to quantify the particle currents to the probe. Extensive derivations of these currents can be found in Engwall (2006). Here we will only give the expressions for different important currents for probes and describe how all the currents balance at a certain potential, which is called the floating potential of the probe. It should be noted that the currents are exactly determined for spherical and cylindrical probes under certain conditions and that the currents are dependent on plasma density and temperature as well as on probe potential. The probe theory is also the basis for understanding spacecraft charging, which is discussed in Section 6.2.1.
CHAPTER 6. MEASUREMENT TECHNIQUE

6.1.1 Probe currents in Maxwellian plasmas
The quantification of the probe currents in low-density plasmas is based on the orbital motion limited theory, OML (Mott-Smith and Langmuir, 1926). This theory simply regards a distribution of particles moving in the vacuum field from the probe, and the trajectories are thus determined only by conservation of energy and angular momentum. This approach can be adopted when the radius of the probe is much smaller than the Debye length. If the probe radius, on the contrary, is much larger than the Debye length, the probe will be efficiently shielded and sheath limited theory (SL) must instead be used. In the following, we will only regard OML theory in unmagnetized plasmas (gyro-radius much larger than the probe) and apply it to spherical probes, noting that it is fully developed also for cylinders.

6.1.1.1 Random current
The random current is the current to a probe at zero potential, and is given by

\[ I_{\text{th}} = 4\pi a^2 n q \sqrt{\frac{K T}{2\pi m}} = 2 nqa^2 \sqrt{\frac{2\pi KT}{m}}, \]  

(6.1)

where \( a \) is the radius of the spherical probe, and \( m \) and \( q \) are the mass and charge of the particle species. If the ion and electron temperatures are of the same order of magnitude, the electron current will be much larger than the ion current, since the ion mass is much larger than the electron mass. This means that a probe immersed in a plasma will charge negatively, if there are no other current sources.

6.1.1.2 Current to charged probe
The current to a charged probe at potential \( V_p \) is given by

\[
I = \begin{cases} 
I_{\text{th}} \left( 1 - \frac{qV_p}{K T} \right) & \text{(attractive potentials, } qV_p < 0) \\
I_{\text{th}} e^{-\frac{qV_p}{K T}} & \text{(repulsive potentials, } qV_p > 0) 
\end{cases}
\]

(6.2)

where \( I_{\text{th}} \) is the random current as shown in equation (6.1). When \( V_p = 0 \), \( I = I_{\text{th}} \) as expected.

6.1.1.3 Photoelectron current
For sunlit probes, in addition to plasma ion and electron currents, we have to regard the photoelectron current.\(^1\) In magnetospheric plasmas the photoelectron current is dominating, which brings the probe to a positive potential. The photoelectron current depends on the projected area of the probe to the Sun,

\[^1\text{In a rigorous treatment other effects, such as secondary electron emission, should also be treated (Garrett, 1981; Eriksson et al., 1999). These currents are included in Section 6.2.1.}\]
$A_p$, the surface properties of the probe, local plasma conditions, distance to the Sun and the solar UV flux. Because of these different dependences, there are many different expressions used for the photoelectron current. In this treatment, we adopt the expressions for spherical probes given by Grard (1973).

For negative potentials all photoelectrons can escape from the probe and the photoelectron current will be saturated at the constant value $I_{ph}^0$:

$$I_{ph} = I_{ph}^0 = A_p j_{ph}^0 \quad (V_p < 0),$$

where $j_{ph}^0$ is the photoelectron current density, which has to be estimated from satellite data. The current density shows large variations and can be in the range $j_{ph}^0 = 1.5 - 8 \text{ nA cm}^{-2}$ (Laakso et al., 1995, and references therein). The main reason for this variation is the highly variable solar UV flux (Eriksson and Winkler, 2007; Pedersen et al., 2008).

Probes at positive potentials will recollect some of the photoelectrons, the more the higher the potential is. The photoelectron current for a spherical probe at positive potential can be approximated by the analytic function (Grard, 1973)

$$I_{ph} = I_{ph}^0 \left(1 + \frac{eV_p}{KT_{ph}}\right) \exp\left(-\frac{eV_p}{KT_{ph}}\right) \quad (V_p > 0),$$

assuming that the probe is smaller than the Debye length and that the photoelectron distribution is Maxwellian. $T_{ph}$ is the photoelectron temperature, which is on the order of 1.5 eV.

### 6.1.1.4 Current balance

Combining the photoelectron current with the expressions for the electron and ion currents, current-voltage relations for the probes can be derived. At equilibrium, the currents will balance each other ($\sum n I_n = I_e + I_i + I_{ph} = 0$) and the probe will attain its floating potential. For sunlit probes operating above the Earth’s ionosphere, the ion current is negligible and the floating potential is in practice obtained by balancing the current of escaping photoelectrons and impinging plasma electrons. In the magnetosphere, the floating potential is normally a few tens of volts positive (Laakso et al., 2002; Lindqvist, 1983). Figure 6.1 shows the current balance for ambient plasma electrons (blue) and escaping photoelectrons (red) to a spherical probe (radius 4 cm) in a magnetospheric plasma of temperature 10 eV and density $10 \text{ cm}^{-3}$. In such an environment, the ion current is negligible. The photoelectron current density is assumed to be $6 \text{ nA cm}^{-2}$. The currents balance each other at approximately 8.3 V positive.
Figure 6.1: Current balance of impinging plasma electrons and escaping photoelectrons to a probe of radius 4 cm. The thermal energy of the plasma is 10 eV and the density is 10 cm$^{-3}$. The photoelectron current density is 6 nA cm$^{-2}$. In such a tenuous plasma the ion current is negligible. The floating potential is around 8.3 V.

For a probe in shadow, the situation becomes very different. In this case the probe will be at negative potential and if the ion and electron temperatures are equal the current balance equation reduces to

$$Me^x + x - 1 = 0,$$

where $x = eV_p/KT_e$ and $M = \sqrt{m_i/m_e}$, $m_e$ and $m_i$ being the electron and ion mass respectively. The numerical solution of the equation for protons is $x = eV_p/KT_e \approx -2.5$. The negative potential is, as explained earlier, due to the difference in mass between electrons and ions, resulting in that the electrons will move faster than the ions and thus hit the probe more frequently.

6.1.2 Probe measurements of densities and temperatures

Langmuir probes have been used for measurements of plasma densities, temperatures and electric fields in space since the beginning of the space era, and even earlier in laboratory plasmas. They still form the basis in many important measurement techniques. In this thesis, we will focus on double-probe electric field instruments, but probe measurements of densities and temperatures also deserve a brief introduction.

To measure the temperatures and densities in a plasma ($n_i$, $n_e$, $T_i$ and $T_e$) a method of voltage sweeps is used. In this mode a bias voltage applied to the Langmuir probe is varied, while the total current to the probe is measured, which produces a current-voltage curve. Fitting the analytical expressions for the electron, ion and photoelectron currents (see e.g. equations 6.2, 6.3 and
6.1. PROBE MEASUREMENTS OF PLASMA

6.4) to this measured curve, we can retrieve estimates of the densities and temperatures.

Two examples of large spacecraft missions currently implementing Langmuir probes for density and temperature measurements are the Cassini and Rosetta spacecraft. Cassini explores the surroundings of the giant planet Saturn, its ring planes and its largest moon Titan. Data from the Cassini Langmuir probe have provided new results on among others the cold plasma in the ionosphere of Titan (Wahlund et al., 2005). Rosetta is sent out to follow a comet on its journey from far out in the solar system towards the hot Sun, where large parts of the icy nucleus have been vaporised. The Langmuir probe will measure the densities and temperatures in the coma of the comet (Eriksson et al., 2007b).

6.1.3 Electric field measurements with double probes

Measurements of electric fields are crucial for the understanding of the environment in space. Together with the magnetic fields, the electric fields determine the motion of the plasma particles. One of the most common techniques for electric field measurements is the double probe technique, which has been well summarised by Pedersen et al. (1998). Additional information can be found in Pedersen et al. (1984), Mozer (1973), Fahleson (1967) and Cully et al. (2007).

6.1.3.1 Measurement technique

The double-probe instrument uses a conceptually simple technique of measuring the potential difference between two probes in a plasma. A simplified picture of the double-probe electrical system is given in Figure 6.2. For electric field measurements, we are interested in the potential difference \( \Phi_1 - \Phi_2 \). The electric field is obtained by dividing this difference with the probe separation. However, it is only possible to measure the quantity \( U_1 - U_2 \), which equals \( (\Phi_1 - \Phi_2) + (V_1 - V_2) \), where \( V_1 \) and \( V_2 \) are the potentials of the probes with respect to the plasma. The double-probe technique is based on the assumption that the coupling between plasma and probe is the same at the two probes, i.e. \( \Phi_1 = \Phi_2 \).

\[
U_1 - U_2 = \Phi_1 - \Phi_2. \tag{6.6}
\]

To achieve this situation there are some requirements that have to be fulfilled (Pedersen et al., 1998; Fahleson, 1967):

1. \textit{Equally shaped probes}. The probes should be equally shaped to avoid that the probe sheaths become different.
2. \textit{Large probe separation}. The separation between the probes should be large to avoid that the probes disturb each other or, more likely, are affected by the spacecraft. The only practical solution is to mount the probes on
wire booms, which are deployed from a spinning spacecraft. A spinning spacecraft leads to an additional requirement: If the spin axis is not directed towards the Sun, the probes should be spherical, so that the photoemission does not vary with the spin.

3. *Same material and electrical loading.* The probes should be constructed with the same surface material and same electrical loading.

The measured electric field from a double-probe instrument is the electric field in the spacecraft rest frame. The electric field in the Earth’s rest frame, $E$, is obtained from the measured electric field, $E'$, using the formula

$$E = E' - v \times B,$$

(6.7)

where $v$ is the velocity of the spacecraft in the Earth system and $B$ is the Earth’s magnetic field (*Fahleson*, 1967; *Mozer*, 1973). This means that for measurements of the electric field in a frame of reference independent of the spacecraft motion, we also need detailed measurements of $v$ and $B$. For a rotating spacecraft with radially deployed probes, it is the spin plane component of the electric field that is measured. To obtain the full electric field vector, it is normally a good assumption to take $E_\perp \gg E_\parallel$, at least for quasi-DC fields. If $B$ is not too close to the spin plane, the total field can be constructed from the spin plane component and the relation $E \cdot B = 0$. One double-probe system on a spinning spacecraft is normally sufficient to determine the full electric field vector. However, it will take one spin period, which will prevent measurements of rapidly varying electric fields. If two double-probes are used instead, the total electric field vector can be determined immediately and the only limitation is probe function and telemetry (*Pedersen et al.*, 1998).

For measurements in a dense plasma the electron and ion currents are sufficiently high to give a good coupling between probe and plasma. In a tenuous plasma, photoemission is essential for satisfactory probe-plasma coupling, which means that the probes have to be sunlit to function. As can be seen in Figure 6.1, the probes float at a relatively high potential where the slope of the photoelectron current is small. This means that a small spurious current to one
of the probes can result in a large false electric field. It is therefore desirable to bring the probe closer to the plasma potential, where the current-voltage curve is steeper, which can be achieved by applying a bias current from the probe to the spacecraft.

Even though the photoemission provides the necessary coupling between probe and plasma, it also introduces new errors into the measurement: If the booms are at the same potential as the spacecraft, which is normally the case, the probe farthest away from the Sun will lose more photoelectrons to the booms than the probe closest to the Sun (see Figure 6.3). This phenomenon creates a spurious sunward electric field. To reduce this asymmetric current of photoelectrons, the booms are commonly constructed with a negatively biased guard close to the probe (Pedersen et al., 1984). The guard will also decrease leakage currents from the spacecraft photoelectrons to the probes and too much influence from the boom potential on the electric field measurement (Cully et al., 2007). Thus, the guard reduces the effects of asymmetrically emitted photoelectrons, but nevertheless there will always be a small sunward offset in double-probe data. For Cluster this offset is around 1 mV/m. It is analyzed in more detail in Paper III.

![Figure 6.3](image_url)

*Figure 6.3:* The probe farthest away from the Sun will lose more photoelectrons to the positively charged booms than the probe closest to the Sun, which will cause a spurious sunward electric field. The errors can be decreased by applying a negatively biased guard near the probes. (After Pedersen et al., 1984, with kind permission from Springer Science and Business Media.)

The surface of the spacecraft has to be sufficiently conductive to serve as a good reference for the double-probe instrument and the current bias system. In addition, a less conductive surface would create differential charging of the satellite, giving rise to a spurious anti-sunward electric field (Pedersen et al., 1984). For a spacecraft with sufficiently conductive surface, the double-probe instrument also provides two useful by-products (Pedersen et al., 1984, 2001):

- **The spacecraft potential.** The spacecraft potential can be determined with an accuracy of a few volts from the potential between the probe and the spacecraft (Cully et al., 2007). This is useful for interpreting data from particle instruments, and can also be used to derive the plasma density (see below).
- **The plasma density.** The plasma density can be related to the spacecraft potential through the current relations derived in Section 6.1.1, since the floating potential of the spacecraft will be very close to that of an unbiased probe. To get an empirical relation between the plasma density and the
spacecraft potential for a specific satellite, the spacecraft potential is com-
pared to the plasma density derived from an on-board density instrument
(Pedersen, 1995; Escoubet et al., 1997; Pedersen et al., 2001, 2008). The
advantage of using the spacecraft potential for density measurements is the
high sampling frequency and the simplicity to interpret the resulting data.
It should be noted that the density alone does not determine the spacecraft
potential: the temperature is also a factor, so the temperature has to be as-
sumed to stay within some range for a plasma density-spacecraft potential
calibration to be valid.

6.1.3.2 Complications

Known sources of spurious electric fields influencing measurements by
double-probe instruments include:
1. Asymmetries of the probes.
2. Coupling between probes and boom tips.
3. Wake effects.
4. Magnetization of the plasma.
5. Plasma density gradients.

How to minimize effects of the two first items has already been treated in the
previous section. The influence of wakes is covered in Section 6.3.3.

Magnetization could complicate the measurements, when the electron
gyroradius is comparable to or smaller than the probe dimensions (Fahleson,
1967). In such a case, the probes will mostly collect electrons from a column
parallel to the magnetic field. Gradients in the plasma density along the boom
direction will cause spurious electric fields, since the basis of the assumption
$V_1 = V_2$ is that the plasma is homogeneous. This error can be reduced by
applying an appropriate bias current (Laakso et al., 1995).

6.2 Spacecraft-plasma interactions

Spacecraft interact with the particles in the surrounding plasma with many
consequences for both the spacecraft itself and the plasma environment. One
of the phenomena of great importance is spacecraft charging. Another effect,
which has already been mentioned briefly in connection with complications
for double-probe electric field instruments, is wake formation behind space-
craft.

6.2.1 Spacecraft charging

The area of spacecraft charging has been subject to extensive research, espe-
cially for commercial satellites, since the potential of a spacecraft in a dense
plasma with very energetic ($\sim 10$ keV) electrons can reach high negative va-
lues on the order of kilovolts. If the spacecraft is charged unevenly, hazardous
electrostatic discharges between different parts of the spacecraft may occur, which will affect the performance of the satellite. The problem of uneven charging can often be solved by using a conductive surface on the spacecraft. Nevertheless, spacecraft charging and discharges remain an issue, especially for certain elements, which for some reason are isolated, and for specifically vulnerable parts of the spacecraft, such as solar panels. The term spacecraft charging has mainly been attributed to cases with high (kV) negative potentials. In this Section we will treat the process behind all types of charging of spacecraft, regardless of the resulting potential.

What makes the spacecraft charge at all? The process of spacecraft charging can be understood by probe theory: we just exchange the probe for the much larger spacecraft and the qualitative picture of currents to the probe/spacecraft remains the same. However, we have no exact analytical expression for the currents in this case, since spacecraft seldom are perfectly spherical or cylindrical. To get quantitative estimates of the spacecraft charging level we therefore have to go to numerical simulations.

As we saw for the probes, an object immersed in a plasma will be hit by the plasma particles due to their thermal motion. The particles are collected by the object, and at thermal equilibrium it will become negatively charged, since the electron current exceeds the ion current at zero potential and equal ion and electron temperatures. As was stated in Section 6.1.1.3, photoemission is important in sunlit parts of the magnetosphere. There exist also further charging effects, which can become important in special cases. Including these additional charging effects, the current balance equation (see Section 6.1.1.4) takes the form

$$\sum_n I_n = I_e + I_i + I_{se} + I_{si} + I_{ph} + I_b = 0.$$  (6.8)

$I_e$, $I_i$ and $I_{ph}$ are, as in the probe case, the electron, ion and photoelectron current, respectively. The currents $I_{se}$ and $I_{si}$ consist of secondary electrons, emitted when electrons and ions hit the spacecraft. In most cases for sunlit magnetospheric spacecraft, the secondary electron emission is negligible compared to the photoelectron current $I_{ph}$. In sunlit magnetospheric plasmas, the photoelectron current will be dominant over all other currents at zero potential and the spacecraft will reach a positive potential, where most of the photoelectrons are re-collected by the spacecraft, and it is only the small fraction of high energy photoelectrons escaping into the ambient plasma that will establish an equilibrium with the other currents (Torkar et al., 1998). $I_b$, finally, is the current from a possible active ion source installed on the spacecraft, which is used for example for propulsion or potential control. An example is ASPOC, the potential control device on board Cluster, which operates successfully to reduce the several tens of volts positive spacecraft potential to constant values of a few volts (Torkar et al., 2001). The potential control makes it possible
to measure low energy ions. In addition to these currents, there could also be currents between adjacent surfaces, if they are charged to different potentials. One may also have to consider displacement currents for time-dependent problems.

As was mentioned in Section 6.1.3.2, the spacecraft potential can be used to measure the plasma density. Pedersen et al. (2001) extracted a potential-density relation for the Cluster spacecraft, which is shown in Figure 6.4 together with the same relation for the Polar spacecraft. Recently Pedersen et al. (2008) have refined the Cluster potential-density relation for low-density plasmas. In general, the potential increases with decreasing density. This is because the photoelectron current dominates more and more, when the density and thus the electron current decreases.

Figure 6.4: Spacecraft potential-density relation for the Cluster and Polar spacecraft. (After Pedersen et al., 2001.)

6.2.2 Wake effects

How does a wake form behind a spacecraft in a flowing plasma? A necessary condition for wake formation is that the flow is supersonic with respect to the ions, i.e. the flow kinetic energy of the ions, \( E_k^i = \frac{mv_i^2}{2} \), exceeds their thermal energy, \( KT_i \). When an object is placed in a supersonic ion flow, a wake void of ions will be created behind the object. This arises because the spacecraft is acting as an obstacle to the flowing ions, and since their thermal speed is lower than the speed of the flow, the cavity will not be filled immediately. Figure 6.5(a) gives a schematic illustration of this phenomenon.
6.2. SPACECRAFT-PLASMA INTERACTIONS

Figure 6.5: Schematic picture of wake formation. (a) The ion kinetic energy, $E_k^i = mv_i^2/2$, exceeds the equivalent spacecraft potential, $V_s$, and a narrow wake is formed. (b) In the case when the ion kinetic energy is lower than the equivalent spacecraft potential, the ions will scatter off the positively charged spacecraft creating an enhanced wake.

If the flow is not only supersonic for the ions, but also subsonic for the electrons ($E_k^e < KT_e$), the electrons will be able to access the wake region, thus giving rise to a negatively charged wake behind the spacecraft. If the thermal energy of the electrons is close to the ion kinetic energy, the negative charge will affect the motion of the ions considerably, thus changing the shape of the wake. Flows subsonic with respect to the electrons and supersonic for the ions appear in the polar wind, but also in the dense solar wind and in the ionosphere, where wakes normally have been studied. The high plasma density in the solar wind makes it different from the tenuous polar wind, however, since it will ensure a low spacecraft potential. Thus, in the solar wind the spacecraft potential will not exceed the ion flow energy ($eV_s < E_k^i$). Therefore the ions will only see the spacecraft body as the obstacle (Eriksson et al., 2007a). In the ionosphere, the plasma is even more dense, and the spacecraft will therefore charge negatively. This will focus the ions into the wake, enhancing the filling-in process of the wake.

In cold tenuous plasmas the situation can be quite different, since the low-density plasma results in such a high spacecraft potential that it may exceed the ion kinetic energy. The flowing ions will then obey the following inequality:

$$KT_i < E_k^i < eV_s.$$  \hspace{1cm} (6.9)
The high spacecraft potential will prevent the ions from reaching the spacecraft and the potential structure, rather than the physical shape of the spacecraft, will act as an obstacle for the ions. Moreover, the ions will be deflected by the spacecraft potential like in Rutherford scattering. These two factors will enhance the wake behind the spacecraft body (see Figure 6.5(b)). A large negatively charged wake will therefore be formed behind the spacecraft.

6.3 Wake effects in Cluster electric field data

6.3.1 The Cluster satellites

The Cluster mission consists of four identical scientific spacecraft investigating space- and time-varying phenomena in the Earth’s magnetosphere (Escoubet et al., 2001). In 1996 the first four Cluster satellites (Cluster I mission) were launched with the first Ariane-5 rocket. Unfortunately, this mission met a premature end, when the rocket failed only 37 seconds after launch. The second attempt in the summer of 2000 was more successful and the Cluster II mission has now been fully operational for more than eight years. The Cluster mission is regarded as a key mission for the European Space Agency, ESA, and has up to date provided a vast range of data.

The four satellites are orbiting the Earth in a formation, which is tetrahedral for as large part of the orbit as Kepler’s laws permit, allowing simultaneous measurements at different locations in the magnetosphere. Each satellite carries 10 instruments for charged particle detection and field and waves measurements. The main goal of the Cluster mission is to investigate phenomena in the following key regions of the magnetosphere: the solar wind, the
6.3 WAKE EFFECTS IN CLUSTER DATA

bow shock, the magnetopause, the polar cusp, the magnetotail and the auroral zones. To achieve this goal, the satellites have elliptical polar orbits. The initial perigee and apogee were at 4 $R_E$ and 19.6 $R_E$, thus passing through all the key regions in a period of 57 h (see Figure 6.7). The satellites are cylindrical with a height of 1.3 m and diameter of 2.9 m. Their launch mass was 1200 kg, of which 650 kg was propellant and 71 kg scientific payload. The satellites are spinning with a period of 4 s.

Figure 6.7: The orbit of the four Cluster satellites during northern fall months. The satellites cover a large region of the magnetotail lobes. (Credits: ESA.)

6.3.2 Electric field measurements from Cluster

The Cluster satellites are equipped with two instruments for electric field measurements using different techniques: the Electric Fields and Waves instrument (EFW) (Gustafsson et al., 1997, 2001) and the Electron Drift Instrument (EDI) (Paschmann et al., 1998, 2001). EFW is a double-probe instrument, the principles of which have been treated in Section 6.1.3. The EFW probes are mounted on thin wire booms, which are deployed radially by the spinning energy of the spacecraft, resulting in a probe-to-probe separation of 88 m. Since the probes are confined to the spin plane, the data from EFW provides only information about the component of the electric field in this plane. The probes are 8 cm in diameter and the diameter of the wire booms is 2.2 mm. Each of the satellites carries two pairs of probes with the booms perpendicular to each other, to be able to measure the electric field up to high frequencies. A bias current is applied between the spacecraft and the probes, which brings the potential of the probes to around +1 V with respect to the local plasma. On the
booms a guard is placed to prevent asymmetric currents of photoelectrons to the booms (see Figure 6.3).

The Electron Drift Instrument is based on a technique determining the drift of high-energy electrons in a magnetized plasma (see Figure 6.8). Two beams of keV electrons are emitted from electron guns on the spacecraft. If a sufficiently strong (at least 30 nT) magnetic field is present, the electrons will experience a magnetic force strong enough to make it possible to regain the electrons at detectors on the spacecraft. The electric field in the plasma will make the electrons $E \times B$-drift. Detecting the drift of the two electron beams, the electric field can be extracted, as long as reliable magnetic field data are available.

![Figure 6.8: The Electron Drift Instrument uses the drift of electrons in a magnetized plasma to measure the electric field. Two high-energy electron beams are emitted from the spacecraft to measure the drift. (After Paschmann et al., 2001.)](image)

Both instruments experience problems in some regions of the magnetosphere. Fortunately, the problems occur in different regions for the two instruments, making them complement each other well. An extensive comparison between EDI and EFW was carried out by Eriksson et al. (2006). In short, EDI will evidently not function for too weak magnetic fields. It will also have problems for rapidly varying magnetic and electric fields, which can be encountered for example in the auroral regions. In these regions, EDI often also have problems with naturally accelerated auroral electrons of keV energy saturating the EDI detectors, thus making it impossible to identify the emitted beam electrons. EFW will give accurate measurements in these regions, due to the construction with two spinning crossing booms, which allow high frequency measurements. On the other hand, EFW measurements can be affected by the influence of the positive spacecraft potential on the plasma environment. This
is especially the case in cold, tenuous plasmas, where enhanced wakes may form.

### 6.3.3 Influence of wake on Cluster EFW

Comparisons with electron drift instruments on different spacecraft have shown that formation of a wake behind the spacecraft and booms can severely affect the measurement from double probe instruments \citep{Bauer1983, Pedersen1984, Eriksson2006}. The plasma is flowing perpendicular to the ambient electric field (in the $\mathbf{E} \times \mathbf{B}$ direction and also parallel to $\mathbf{B}$), which means that the spurious wake electric field will be transverse to the real ambient electric field (assuming the parallel electric fields are negligible). In the plane perpendicular to $\mathbf{B}$ the wake will have more influence on the direction than on the amplitude of the measured electric field component in this plane, provided that the wake field is not too strong. However, the wake induced field along $\mathbf{B}$ may be many orders of magnitude above any real parallel electric field. This is the case in e.g. the polar wind, where spurious electric fields due to wakes have been observed in Cluster data \citep{Eriksson2006}.

Wakes behind Cluster are common in the double-probe data, both in the solar wind and in cold tenuous plasma flows in the magnetotail lobes. As was described in Section 6.2.2, the wakes in the solar wind are narrow and can therefore be easily detected in EFW data as a distinct peak, when one of the probes passes the wake. In cold tenuous plasmas, where the wakes are enhanced, the situation is completely different: the wakes are so wide that the wake field cannot easily be sorted out from the background field and the EFW data are strongly contaminated by the wake field. However, if EDI is operating well, it is possible to determine the size of this spurious field, which in some regions can reach up to 10 mV/m. In Figure 6.9 electric field data from Cluster in the polar cap at a geocentric distance of 8.6 $R_E$ is shown. In the upper panel the spacecraft potential is displayed, while the two lower panels show the electric field components $E_x$ and $E_y$ in GSE (Geocentric Solar Ecliptic) coordinates for EDI (blue) and EFW (red). The component $E_x$ is almost aligned with the magnetic field lines, along which ionospheric escape. $E_y$ is perpendicular to $E_x$ and consequently also roughly perpendicular to the plasma flow. As can easily be seen, the measurements from EFW is mainly disturbed for $E_x$, thus in the direction of the low-energy plasma flow. The errors also grow when the spacecraft potential increases. These two facts provide evidence for an enhanced wake behind the spacecraft creating the spurious electric field in the EFW data.

The formation of enhanced wakes and its influence on the EFW instrument is the subject of Paper I of this thesis. In this paper, we have made rough theoretical estimates of the size of the wake and performed numerical simulations of the wake formation. In Paper II, we investigate in detail the influence of
Figure 6.9: Electric field data from the polar cap at a geocentric distance of 8.6 $R_E$. The upper panel shows the spacecraft potential and the two lower panels show comparisons of the electric field as measured by EDI (blue) and EFW (red). $E_x$ is in this case approximately in the same direction as the plasma flow, while $E_y$ is roughly perpendicular to this direction. Note that EFW experiences problems mainly in the $E_x$-direction and that the errors grow when the spacecraft potential is high. (The electric field components are given in the GSE coordinate system.)

the wake on the spin signatures of EFW, the results of which can be useful for detection of wake fields in EFW data. The wake studies have paved the way for a new method using the spurious electric field, which was first seen merely as a complication, to study cold ions. The method is described in the next section, and the study of cold plasma flows with electric field instruments is the subject of Papers III-V.

6.4 Studying cold plasma flows with electric field instruments

As has been described in Section 5.1, it is difficult to measure the properties of magnetospheric low-energy ions with particle detectors mounted on a spacecraft, since the ions often do not possess enough energy to surmount the positive satellite potential. Here we present the basic principles of our new method to study cold plasma flows with electric field instruments. A detailed description of the method can be found in Paper V.

By studying the electric field signature of the enhanced wake forming behind the Cluster spacecraft in cold, tenuous plasma flows, we are able to detect the previously invisible cold ions in the geomagnetic lobes from a few $R_E$ from
the Earth to as far as almost 20 \( R_E \). Since the ions are unmagnetized on the wake length scale, the wake electric field, \( E^w \), will be in the flow direction:

\[
E^w = E^{EFW} - E^{EDI} = gu,
\]  

(6.10)

where \( u \) is the flow velocity and the scalar \( g \) may be a function of, for example, the spacecraft potential, the ion temperature and the flow speed \( u \), but should be independent of the flow direction. Provided that the frozen-in condition applies, the perpendicular drift velocity of the ions is given by \( \mathbf{u}_\perp = E^{EDI} \times \mathbf{B}/B^2 \). The parallel velocity can then be obtained by decomposition of \( E^w \) in the two measured components \( x \) and \( y \) in the spacecraft spin plane, and by subsequent division of \( E^w_x \) with \( E^w_y \):

\[
E^w_x = \frac{gu_{\perp,x} + gu_{\|}B_x/B}{gu_{\perp,y} + gu_{\|}B_y/B}.
\]  

(6.11)

Rearrangement gives the velocity along \( \mathbf{B} \)

\[
u_{\|} = \frac{E^w_x u_{\perp,y} - E^w_y u_{\perp,x}}{E^w_y B_x - E^w_x B_y}.
\]  

(6.12)

To determine the flux, we need the density of the outflowing ions. For this purpose, we use the recently developed spacecraft potential-density relations by Pedersen et al. (2008) with a refinement to compensate for variations due to the difference in solar radiation (Paper V).

The velocity calculation was validated in Paper III, where we apply the method on an event in the geomagnetic tail at a geocentric distance of 18 \( R_E \). At the same time, use of artificial spacecraft potential control made it possible to measure the flow speed with the ion spectrometer CIS (Rème et al., 2001) in low-energy mode on board another of the Cluster satellites. The results from our method and from the particle detector show good agreement, and even though we have only been able to make simultaneous measurements for one event, this confirms that the method actually works. In Papers IV-V, we have used the method for extensive statistical studies in the lobes, yielding many interesting results. The most important findings are presented in Chapter 7. Here we just reproduce one important figure (Figure 7 of Paper V), showing a map of the density and velocity of the outflowing ions in the GSM (Geocentric Solar Magnetospheric) X-Z and X-Y planes (see Figure 6.10). The density is higher closer to the Earth and the velocity increases farther away from the Earth. This figure confirms the qualitative picture of outflowing ions obtained from simulations (e.g. Delcourt et al. (1989) and Huddleston et al. (2005)), but is the first to be based on satellite measurements in situ.
Figure 6.10: Density and velocity maps of outflowing ions. The mean density and velocity are shown in the GSM X-Z and X-Y planes. The data are grouped in 2 $R_E$ by 2 $R_E$ bins. A bin is coloured if the number of points in the bin exceeds approximately 350 (30% of the mean number of points in a bin). The direction of the magnetic field is shown in white. (The total data set consists of 180,000 points.)
Chapter 7

Summary of papers

Paper I

E. Engwall, A. I. Eriksson, and J. Forest

Wake formation behind positively charged spacecraft in flowing tenuous plasmas


We report results from a study of enhanced wake formation behind positively charged spacecraft in flowing tenuous plasmas using rough analytical estimates and numerical simulations. For the numerical simulations we have used the code package PicUp3D (Forest et al., 2001). These simulations have provided new knowledge on the size and shape of the wake, as well as scaling to different plasma parameters. The most evident results are that (a) a low ion temperature causes a large ion wake, and (b) a high electron temperature leads to a more negative potential in the wake. We have modeled the spacecraft body and the spacecraft booms separately, which makes it possible to investigate which part creates the largest wake. Even for very thin wire booms (thickness on the order of a few millimeters), the wake can grow very big, since the potential structure around the booms will increase the effective size of the obstacle to the plasma flow with three orders of magnitude. Around the spacecraft body the potential decreases much more quickly. This was evident in the simulations, showing a much more negative wake potential behind the booms than behind the spacecraft body.

Moreover, we have compared the simulation results to measurements from the Cluster double-probe instrument EFW, where we suspect influence from an enhanced wake (Eriksson et al., 2006). We have seen that the magnitude of the suspected wake field detected by EFW is consistent with the simulation results. The wake spin signatures of EFW have also been well reproduced by the simulations, further supporting the idea of enhanced wake formation behind Cluster.
My contribution to Paper I: I performed the simulations, compared the simulation results to satellite data and had the main responsibility for writing the paper.

Paper II

E. Engwall, and A. I. Eriksson

Double-probe measurements in cold tenuous space plasma flows


In this paper we discuss the two main sources for spurious electric fields disturbing double-probe measurements in cold flowing tenuous space plasmas: (1) asymmetric photoemission between probes and other electrical elements of the spacecraft, and (2) enhanced wakes. By performing a Fourier analysis of EFW spin data, we have found that the photoasymmetric field, $E_a$, can be represented by

$$E_a(\theta) = E^0_a \cos \theta,$$

where $\theta$ is the angle between the boom and the direction to the Sun. In the case of Cluster the amplitude of the photoasymmetric field is typically around 1-2 mV/m.

Furthermore, we assume that the wake field can be written as

$$E_w = a_{w1} \cos \theta_b + a_{w3} \cos(3\theta_b) + a_{w5} \cos(5\theta_b),$$

where $\theta_b$ is the angle between the boom and the wake direction. Now, Fourier analysis of EFW spin data including wake effects makes it possible to determine the angle of the wake, as well as the Fourier coefficients $a_{w1}$, $a_{w3}$ and $a_{w5}$. We have seen that the Fourier coefficients are dependent on satellite potential: the signatures become more sinusoidal for higher satellite potentials, which is expected for an enhanced wake field.

The method could in theory be used in subsequent studies to more precisely determine the direction of the wake, which is used in the velocity calculation. However, in practice, when analyzing large data sets, we found that the method was difficult to implement on a routinely basis, at the same time as the gain was relatively small.

My contribution to Paper II: I developed the theoretical model and verified it with satellite data. I also had the main responsibility for writing the paper.
Paper III

E. Engwall, A. I. Eriksson, M. André, I. Dandouras, G. Paschmann, J. Quinn, and K. Torkar


We present a case study of cold ions detected by Cluster in the magnetotail lobes at 18 $R_E$. The ions are so low in energy (order 10 eV) that they are not normally detectable by ordinary particle instruments due to high positive spacecraft potentials (40-60 V). However, for this event, artificial spacecraft potential control reduces the spacecraft potential to around +7 V and the Cluster ion detector is in a special low-energy mode, making it possible to measure the cold ions. At the same time we are able to detect and derive the flow velocity of the cold ions using electric field instruments. The method is based on the enhanced wake formation behind a positively charged spacecraft in a flowing tenuous plasma.

The good agreement between the two methods shows that a simple model of the wake field in combination with electric field data from double-probe and electron drift instruments can be used to estimate the flow velocity of low-energy, supersonically flowing ions. The flow measurements using both methods are in accordance with the polar wind survey at 8 $R_E$ by Su et al. (1998), confirming the continuation of low-energy ion outflows to at least 18 $R_E$.

**My contribution to Paper III:** I made the data analysis, contributed to the method development and had the main responsibility for writing the paper.

Paper IV

E. Engwall, A. I. Eriksson, C. M. Cully, M. André, R. Torbert, and H. Vaith


We use the method presented in Paper III to make a statistical study of low-energy proton outflows in the geomagnetic tail lobes. Data from one of the Cluster spacecraft (number 3) are analyzed from July to October 2002. During this period, the spacecraft covers large regions of the lobes from 5 to 19 $R_E$. In this region outflowing ions from the polar regions have previously been invisible for spacecraft measurements.
We show that the outflows continue far out to fill the lobes, and that the outflowing cold plasma dominates in both flux and density in this large magnetospheric region. The study also gives evidence for the ionosphere as a major supplier of plasma to the magnetosphere. Since we are able to measure at higher altitudes than in previous studies, we are also able to give a better estimate of the total proton outflow than ever before. It is inferred to be on the order of $10^{26}$ protons/s. In addition, we show that the ions remain cold, which puts strong limits on any acceleration or heating mechanism.

**My contribution to Paper IV:** I planned the study, performed the data analysis and had the main responsibility for writing the paper.

**Paper V**


*Statistics of the cold hidden component of ionospheric outflow determined from 5 to 19 RE in the Earth’s magnetotail*


In this paper we extend the study presented in Paper IV to include much more data covering the fall months (July-October) during the period 2001 to 2005. The results from Paper IV are confirmed in this study. We also investigate the distribution in space of the ion outflow, as well as variations in the ion outflow with different controlling factors, such as solar wind properties and geomagnetic activity.

The ion outflow is concentrated in the central lobes, and few cold ions are detected on the flanks. Along $Z_{GSM}$ the outflow of cold ions decreases towards the neutral sheet, where the ions get heated. There is a dependence on altitude with more or less linearly increasing outflow speed with increasing geocentric distance and approximately exponentially decreasing density and flux. This is consistent with the concept of centrifugal acceleration. The outflowing ions are convected in the dawn-to-dusk direction due to the potential pattern in the polar caps. There is a strong dependence of the outflow on geomagnetic activity and solar illumination. Solar wind parameters, mainly the dynamic pressure and the interplanetary magnetic field, also have strong influence on the rate of outflowing ions.

**My contribution to Paper V:** I planned the study, performed the data analysis and had the main responsibility for writing the paper.
Chapter 8

Summary and Outlook

The Earth’s atmosphere escapes at a rate of a few kilograms per second. Escape of neutrals accounts for the greatest particle flux, whereas the largest mass flux is transported in plasma loss processes. This is because energization processes in the auroral region can remove also species with higher mass, mainly in the form of oxygen ions, while only light neutrals can reach velocities above the escape velocity. Since oxygen is crucial for the survival of life on the Earth, the plasma processes are of special interest. Accretion of matter from interplanetary bodies is on the same order of magnitude as the total loss of the atmosphere. In a typical year, the mass influx consists mostly of submillimetre particles. Over very long time scales big impacts of comets or asteroids dominate the mass flux.

The dominating particle flux in plasma outflows occur at low energies, which makes them difficult to measure at high altitudes with conventional ion spectrometers on board spacecraft due to spacecraft potential screening effects. The high-latitude low-energy ion outflow has therefore previously only been measured close to the Earth. During this thesis work, we have developed a new method utilising the enhanced wake forming behind a spacecraft in low-energy ion flows to study these ions with the Cluster electric field instruments. This has given a very large database of properties of cold ion flows in the Earth’s magnetotail from 5 to 19 RE.

In papers I-II we have examined the wake formation and its influence on the Cluster electric field instruments. Papers III-V present the new method and give statistical properties of the ion outflow. The main conclusions of this thesis can be grouped as follows:

**Wake effects**

1. In cold flowing plasmas, where the condition $KT_i < mv_i^2/2 < eV_s$ is fulfilled an enhanced wake will be formed. This has been quantitatively verified by computer simulations.
2. The electrostatic structure of the wake depends mainly on two parameters:
   (a) Low ion temperature will result in a larger ion wake.
   (b) High electron temperature will create a more negative potential in the wake.

3. The enhanced wake will affect spacecraft borne electric field double-probe instruments. This is evident in the geomagnetic tail lobes, where cold flowing plasmas are frequent. Future spacecraft missions operating in such environments should also carry an alternative instrument for measurements of electric fields, like EDI on Cluster. Double-probe instruments like EFW have instead great advantages in other regions of the magnetosphere (Eriksson et al., 2006).

4. The direction of the wake electric field measured by EDI and EFW can be used to derive the flow velocity of the ions. The method is general and could be applied on other spacecraft, which have comparable electric field instrumentation as Cluster.

**Ion outflows**

5. Cold plasma outflows from the ionosphere constitute a major part of the net loss of matter from the Earth. Since we measure at very high altitudes, our study gives a better estimate of the total loss of protons than ever before. It is inferred to be on the order of $10^{26}$ ions/s. This confirms that the ionosphere is a major contributor of plasma to the magnetosphere.

6. The low-energy proton outflow dominates over the escape of more energetic (>100 eV) protons. We have found that the ions remain cold throughout the lobes, which means that the cold ion flux dominates in this large magnetospheric region.

7. The dominance in density is even more evident, since the low energy ions have lower velocity. Our measurements show that there is a significant population of low-energy ions continuously present in the lobes with a mean density between 5 and 19 RE of 0.18 cm$^{-3}$. This is a much larger number than measured by previous spacecraft missions, since the ions were obscured by spacecraft potential screening effects. Recent results from Mars Express have shown that there exists a cold dense plasma population also around Mars (Dubinin et al., 2008). That study in combination with our results indicate that cold plasma is more important around planetary bodies than previously believed.

8. The ion energy remains low throughout the lobes, which puts strong limits on any acceleration or heating mechanism. The outflow velocity increases approximately linearly with geocentric distance, while the density and flux decrease more like an exponential. This is consistent with centrifugal acceleration.
9. The ionospheric outflows are concentrated in the central lobes, with very few detected outflowing ions on the flanks. In the \(Z_{\text{GSM}}\) direction the occurrence of cold ions decreases towards the neutral sheet, where they get heated. The potential pattern in the polar cap convects the ions in the dawn-to-dusk direction.

10. The rate of ion outflow depends strongly on geomagnetic activity and solar illumination. It is also correlated to several parameters in the solar wind, especially the solar wind dynamic pressure and the interplanetary magnetic field strength.

Quantification and insight of the loss processes from the Earth’s atmosphere are important to get a better understanding of loss processes on other planetary bodies in general, as well as of how atmospheres favourable for life evolve. Recently there has been evidence that the atmosphere of the most studied exoplanet, HD209458b, not only contains hydrogen, oxygen and carbon (Vidal-Madjar et al., 2003, 2004), but also significant fractions of water vapour (Barman, 2007). This suggests that many other exoplanets can host water, which is one of the crucial elements for life. However, the hundreds of exoplanets found so far are not favourable for life as we know it. As an example, the conditions on exoplanet HD209458b are very rough; it is a gaseous planet the size of Jupiter with an orbit very close to the central star. In addition, absorption spectrum of the light from the central star has shown existence of a high-speed hydrogen cloud far from the planet. This is interpreted as either atmospheric hydrogen escaping at a rate \(10^8\) times faster than the Earth’s atmospheric loss (Vidal-Madjar et al., 2003), or energetic neutral atoms produced through charge exchange between the planetary atmosphere and the stellar wind (Holmström et al., 2008).

With the launch of the Kepler telescope in March this year the search for Earth-like exoplanets in our Galaxy will intensify. When such a planet is found, it will not be sufficient to search for signatures of life through spectral analysis of the atmosphere without considering the escape mechanisms from the planet. Therefore the planet should be characterized in terms of e.g. intrinsic magnetic field, mass and distance to the central star to understand if the atmosphere is retained or lost during evolutionary time scales. Current and future spacecraft missions around the Earth, as well as around other planets and moons in the Solar System, will serve as a crucial basis for insight into different aspects of atmospheric escape applicable also to exoplanets.
Jorden läcker syre i rymden

Jorden läcker och varje år strömmar tusentals ton av atmosfären rakt ut i rymden för att aldrig återvända. Det visar ny forskning. ▶ Läs artikeln

Figur 9.1: Vår studie som publicerades i Nature Geoscience fick relativt stort genomslag i svenska medier. Läsarnas intresse var också stort, även om Blondinbellas otillbörliga schamporeklam förståss fick mer uppmärksamhet...
Chapter 9

Sammanfattning på svenska

Jordens atmosfär förlorar kontinuerligt materia som försvinner ut i rymden. En stor del av dessa förluster består av utflöden från polarområdena av joner med låga energier. Det rör sig främst om jonerna H\(^+\) och O\(^+\), vilka strömmar bort i riktning från solen längs jordens magnetiska fältlinjer. Tidigare har man bara kunnat mäta utflödet av väte på mycket låg höjd och därmed har man inte vetat om det för alltid går förlorat ut i rymden eller om det återvänder till jorden. I denna avhandling presenterar vi en metod för att mäta dessa utflöden långt från jorden och det står klart att jorden förlorar tiotusentals ton av atmosfären varje år från polarområdena. Vi visar också att en stor del av materien i rymden nära jorden består av joner med låg energi, vilka tidigare varit osynliga.


Partiklarna i solvinden och magnetosfären är joniserade och utgör ett plasma, som ibland brukar betecknas som det fjärde aggregationstillståndet. Till skillnad från en vanlig gas är atomerna splittrade i joner och elektroner, vilket gör att elektromagnetiska krafter till stor del styr dynamiken i ett plasma. Detta gör att partiklar kan växelverka över mycket stora avstånd. Plasmapartiklarna i solvinden, magnetosfären och jonosfären påverkar på så sätt varandra utan att de kommer i direkt kontakt och detta kan resultera i olika dynamiska processer. Ett synligt exempel är norrskenet, som uppstår genom att laddade partiklar skjuts ner mot atmosfären, där atomer och molekyler exciteras och avger ljus när de återgår till sina grundtillstånd. Ett annat exempel är utflöden av joner från den övre atmosfären, vilka ökar vid förhöjd magnetisk aktivitet och starkare solvind.
Jordens atmosfär består vid jordytan av 21% syre (O$_2$) och 78% kväve (N$_2$). Den resterande procenten utgörs främst av ädelgasen argon. Solens ultravioletta ljus joniserar de neutrala komponenterna i atmosfären och på en höjd över 70 km är den ultravioletta strålningen så stark och kollisioner så ovanliga att jonerna och elektronerna inte återförenas i neutrala atomer och molekyler. Därmed har ett permanent joniserat område bildats. Detta är jonosfären (se Figur 2.4, s. 19).


De beskrivna jonosfärutflödena förväntas fortsätta långt ut i magnetosfärens svans, eftersom en partikel som har en energi som är så hög att den kan övervinna jordens gravitationsfält kan flyga ut ur jordens graviationsfält. Totalt försvinner ungefär 2 kg/s genom dessa två processer.
inte kan nå fram till en jondetektor som monterats på en vetenskaplig satellit. I stora delar av magnetosfärens svans har man därför i princip inte kunnat se några joner.

I den här avhandlingen presenterar vi en ny metod för att mäta dessa joner på hög höjd. Metoden bygger på uppmätning av det utglesade område som uppstår bakom en satellit i ett lågeneretiskt, flödande plasma. Effekten kan liknas vid kölvattnet bakom en båt, med joner som viker av framför satelliten (se Figur 6.5(b), s. 61). På de europeiska Clustersatelliterna (se Figur 6.6, s. 62) påverkar effekten ett av instrumenten för mätning av elektriska fält och till en början trodde man att det var ett mätfel. Med hjälp av data från ett kompletterande instrument gör detta "mätfel" det möjligt att få fram riktningen på flödet och därefter även dess hastighet.

Vi har applicerat metoden på satellitdata från ett stort område i magnetosfären, där joner tidigare varit osynliga (se område 6 i Figur 5.1, s. 38). På så sätt har vi fått många nya spännande insikter om jonosfärutsflöden:

1. Genom att mäta på hög höjd har vi bättre än någonsin tidigare kunnat bestämma det totala utflödet av protoner från jorden. Det är i storleksordningen $10^{26}$ joner i sekunden. Detta visar att plasmautsflöden utgör en stor del av nettoförlusterna från jordens atmosfär samt att jonosfären bidrar i stor utsträckning till plasmat i magnetosfären.

2. De tidigare osynliga jonerne med låg energi har visat sig vara den dominerande beståndsdel i stora delar av magnetosfären. Satelliten Mars Express har med hjälp av ett radarinstrument kunnat visa att det även på Mars finns stora mängder lågeneretiskt plasma, som inte kunnat mättas med partikelinstrument. Tillsammans med våra resultat tyder detta på att plasma med mycket låga energier är betydligt viktigare kring planet än man tidigare trott.


4. Utflödestakten av joner påverkas i stor utsträckning av olika faktorer, däribland hur stark solens UV-strålning är, hur hög den magnetiska aktiviteten är i magnetosfären samt solvidens fart och magnetfält. (Hur utflödena påverkas av magnetfältets riktning i solvidnen visas schematiskt i Figur 5.6 på s. 48.)

Jordens atmosfär väger totalt $5 \times 10^{18}$ kg och i det sammanhanget är utflödena på ett par kg i sekunden eller tiotusental ton per år försvinnande små mängder. Dessutom tillförs jorden materia från bl.a. kometer och meteorider i ungefär lika stor utsträckning som det som går förlorat (se Figur 4.1, s. 34). Utflödesprocesserna som presenteras i denna avhandling är ändå av stort intresse, eftersom de påverkar dynamiken i magnetosfären. Dessutom är de viktiga för att förstå hur andra planeter förlorar sin atmosfär. De kan också ge ökad förståelse kring hur jordens atmosfär har förändrats över långa tidsskalor och därmed också kring hur atmosfärer som är gynnsamma för liv utvecklas.
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Bibliography


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