On the structure and dynamics of Saturn's inner plasma disk

Licentiate Thesis

by

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"If you wish to make an apple pie from scratch, you must first invent the Universe"

- Carl Sagan
1 Introduction

The gas giant Saturn, known for its magnificent rings, have been observed and studied for several thousands of years. Due to its large size it is visible by the naked eye, but a telescope is needed to observe the rings and thus they were not discovered until the 17th century. The nature of the rings was disputed, some argued it to be two moons instead of rings, while others suggested it to be composed of several solid ringlets. In 1859 J. C. Maxwell showed, in the essay "On the stability of the motion of Saturn’s rings", that the rings could not be solid as they would become unstable and break apart. Today we know much more about the physical characteristics of the rings. We know that the ring grains are composed almost entirely of H$_2$O in the form of ice or frost (Nicholson et al., 2008) and we know that the ring particles range from nanometer sized to meter sized, with relatively few exceeding a radius of 5 m (Marouf et al., 1983). The total mass of Saturn’s rings is estimated to between $3\times10^{19}$ and $6\times10^{20}$ kg (Charnoz et al., 2009). This mass is not only due to the solid ring particles but is also due to gas and plasma that surrounds the rings as a ring ionosphere. Figure 1 shows a picture of the night side of Saturn, the Sun can only be seen as the small spark in the lower left edge of the planet. The image shows the different ring segments clearly presented. The rings were named as they were discovered and they therefore come in the order D, C, B, A, F, G, and E, with various ringlets and arcs located in between.

![Figure 1: Cassini image showing the night side of Saturn. The outer ring is the E-ring that is dominated by the moon Enceladus, which can be seen as a white dot embedded in the E-ring material. Courtesy NASA/ESA.](image-url)
The first spacecraft to visit the Saturnian system was Pioneer 11 that made a flyby in 1979. In 1980 and 1981, respectively, Voyager 1 and 2 also passed by on their way further out of the Solar System. But most of our current knowledge of the Saturnian system is based on measurements from the Cassini spacecraft. Cassini went into orbit around Saturn in 2004, the first spacecraft to do so, and are still to the date of writing providing us with new information about Saturn and its surrounding. On board the Cassini spacecraft is a Langmuir probe (LP) that was developed by and are operated by the Swedish Institute of Space Physics (IRF). It is the data from this instrument that is used for the investigation presented in this report. A Langmuir probe is a kind of weather station for space weather, it measures the temperature, density, and speed of the plasma. We use the Cassini LP to investigate the plasma located around Saturn. It is important to understand the different plasma processes so that we can understand the magnetosphere of Saturn and also to be able to compare with and understand other magnetospheres. In order to do this we need to identify and understand plasma sources and sinks, transport mechanisms, and acceleration mechanisms within the Saturnian system.

The Cassini-Huygens mission and the LP on Cassini is shortly described in Section 2 of this report. The two first parts of Section 2 are revised sections from my master thesis ”Determination of Solar EUV Intensity and Ion Flux from Langmuir Probe Current Characteristics” (Holmberg, 2010). Section 3 gives an overview of the theory behind the Langmuir probe and Section 4 gives a more detailed description of the inner magnetosphere of Saturn, including our results. The two published papers that make up the basis of this thesis are summarized in Section 5, and included in the end of the thesis.
2 Cassini-Huygens spacecraft

The Cassini-Huygens mission is a joint mission involving NASA, ESA and the Italian Space Agency (Agenzia Spaziale Italiana, ASI). The first discussions about a mission with the objective of studying Saturn and its moons started in the late 1970’s, but it was not until 1982 that the first Cassini proposal came from a group of European and American scientists in collaboration with NASA. The orbiter Cassini was developed by NASA and ASI contributed with a high-gain communication antenna. An illustration of the S/C is presented in Figure 2, where the ASI antenna is the white dish on the top of the central cylindrical body. Later on the Huygens probe was added to the mission, in Figure 2 illustrated as the golden dish located below the Langmuir probe. The Huygens probe was developed by ESA with the objectives of studying the lower atmosphere and the surface of Saturn’s moon Titan. The Cassini-Huygens S/C was launched in October 1997 and went into orbit around Saturn in July 2004. The primary mission was set to end in 2008, but was extended to 2017. (This section is adapted from Holmberg (2010).)

Figure 2: An illustration of Cassini showing the location of the Langmuir probe. Picture from the article ”The Cassini Radio and Plasma Wave Investigation” by Gurnett et al. (2004).
2.1 The Cassini Langmuir probe

Cassini-Huygens is equipped with 18 instrument packages whereof one is the Radio and Plasma Wave Science (RPWS), which is used to study radio emissions, plasma waves, thermal plasma and the dust around Saturn (Gurnett et al., 2004). One of the main components of the RPWS instrument is the Langmuir probe, which is an instrument that is used to measure the properties of a plasma. The RPWS LP consists of a titanium (Ti) sphere, 5 cm in diameter, with a titanium nitride (TiN) coating. The sphere is mounted at the end of a 0.8 meter long boom that folds out from one of its three legs, which gives the sphere a distance of 1.5 m to the nearest S/C surface. To minimize disturbances, the 10.9 cm of the boom closest to the sphere has a diameter of only 6.35 mm and is held at the same potential as the sphere (Jacobsen et al., 2008). This part is also made of Ti with a TiN coating and is referred to as the stub. The boom, on the other hand, is held at the same potential as the S/C, is electrically isolated from the stub and has a diameter of 9.53 mm (at the interface with the stub). (This section is adapted from Holmberg (2010).)

The Cassini Langmuir probe was developed by the Swedish Institute of Space Physics in Uppsala and has this far supplied us with more than nine years of measurements around Saturn. This has resulted in discoveries such as dust-plasma interaction in the Kronian moon Enceladus’ plume (Morooka et al., 2011) and detection of negative ions in the ionosphere of the Kronian moon Titan (Ågren et al., 2012), among numerous information on the physical properties of the Kronian magnetosphere (e.g. Morooka et al. (2009), Gustafsson and Wahlund (2010), and Holmberg et al. (2012)).

The basic principle behind the Langmuir probe measurements is simple; by applying a positive or negative voltage to the probe the amount of attracted negative or positive particles can be estimated by measuring the generated current. A larger current corresponds to a higher flux of particles and thereby the density of the plasma can be derived. Using various techniques the Langmuir probe can also obtain the plasma temperature, the integrated solar EUV flux, energy distribution of emitted photoelectrons, the spacecraft potential, the flow speed and the mean ion mass of the plasma, and detect dust particles (e.g., Eriksson et al., 2007).

The standard LP measurement technique and the one mainly used for the work presented in this thesis is the voltage sweep. The RPWS LP potential
$U_{bias}$ starts from -32 V and in less than 0.5 s measurements of the current $I$ have been taken in 512 steps while the bias voltage has been raised to 32 V and then decreased to -32 V again. For selected flybys a range of ±4 V is used instead, in order to gain more accurate measurements. RPWS LP sweeps are usually performed every 10 min, so called survey mode, but during flybys of interesting objects, such as Saturn’s moons, the frequency is increased to every 24 s (Wahlund et al., 2009). Data points from such a sweep shows the voltage-current characteristic, an example curve is displayed in Figure 4. More about voltage-current characteristics will be discussed in Section 3.

The following section presents other LP measurement techniques presented by Eriksson et al. (2007). LP measurements may also be performed by keeping a constant bias voltage $U_{bias}$ at the probe and studying the changes in the measured current $I$. By assuming isothermal or adiabatic conditions, the electron density variations can be estimated. Dust particle impacts can be detected through the plasma cloud produced by the impact, which will cause voltage or current pulses in the probe. A third way of performing LP measurements is by a controlled bias current $I_{bias}$, and measuring the potential between the probe and the spacecraft, which depends sensitively on the plasma density. This mode is not implemented for the Langmuir probe on the Cassini spacecraft. It is also possible to let the probe potential float freely, with no applied bias current. If two probes are used, the potential difference between the two probes divided by the probe separation provides an electric field estimate.
This chapter gives a more detailed description of Langmuir probe measurements, the theory behind them and some perturbations that might be encountered while using the Langmuir probe in space.

3.1 Plasma

The Cassini Langmuir probe is used for measuring plasma properties. A plasma is a quasi-neutral ionized gas of charged and neutral particles, which exhibits collective behavior. There are several ways to create a plasma, one way is to heat a gas. If a gas is in thermal equilibrium with the temperature $T$, the density ratio between the neutral molecules and atoms $n_n$ and free electrons $n_e$ are given by the Saha equation

\begin{equation}
\frac{n_e}{n_n} = \left( \frac{2\pi m_e k_B T}{h^2} \right)^{3/4} \frac{1}{\sqrt{n_n}} \exp \left( - \frac{E_i}{2k_B T} \right)
\end{equation}

where $m_e$ is the electron mass, $k_B$ is the Boltzmann constant, $h$ is the Planck constant, and $E_i$ is the ionization energy for the neutrals (Eriksson, 2002). If the gas is heated eventually the atoms and molecules of the gas will start to separate into free electron and ions. If only a small part of the gas is ionized it will still to a large degree be governed by collisions and is therefore just a partially ionized gas and not a plasma. For example, for air at room temperature the density ratio $n_e/n_n \sim 10^{-120}$, for it to become a plasma a much higher value is required (Eriksson, 2002). As more and more of the gas is heated, the ionization rate is low until $E_i$ is just a few times $k_B T$, then it increases abruptly and the gas turns into a plasma (Chen, 1984). A plasma can also be created by exposing a gas to a source of energetic photons, such as UV light or X-rays from the Sun, or by impacts from energetic particles. In order to keep the gas ionized the ionization source must be very strong or the recombination rate low, such as for a very tenuous plasma. That the plasma is quasi-neutral means that it exhibits a roughly equal number of positive and negative charges. This does not necessarily mean positive ions and negative electrons but can also include other components, such as negative ions or charged dust. A plasma exhibits collective behavior, this means that the plasma is dominated by large-scale collective motions when exposed to an electric and/or magnetic field, such a collective motion is for example plasma oscillations (Gurnett and Bhattacharjee, 2005). So collective behavior means that the motion of the charged particles in a plasma are effected not only by local conditions but also by the state of the plasma in remote regions. The
discrete interaction common in a neutral gas, collisions between individual particles pairs, tend to undermine these large-scale motions. The importance of the collective interaction versus the discrete interaction is given by the ratio between the electron plasma frequency $\omega_{pe}$ and the electron collision frequency $\nu_{ei}$,

$$\frac{\omega_{pe}}{\nu_{ei}} = \sqrt{\frac{\pi}{2}} \frac{128n_0\lambda_D^3}{2 \ln(12\pi n_0\lambda_D^3)}$$  \hspace{1cm} (2)

where $n_0$ is the background plasma number density and $\lambda_D$ is the Debye length, see Section 3.2 for a discussion on the Debye length (Gurnett and Bhattacharjee, 2005). If $n_0\lambda_D^3 \gg 1$ the electron plasma frequency $\omega_{pe}$ is much larger than the electron collision frequency $\nu_{ei}$ and the collective oscillations are much more important than the discrete particle effects (Gurnett and Bhattacharjee, 2005). If $n_0\lambda_D^3 \ll 1$ the collective oscillations are rapidly destroyed and strongly damped by collisions of individual particles, such is the case in solids (Gurnett and Bhattacharjee, 2005). Plasma is a very common state for baryonic matter in our Universe, it is the state of matter of stars and also of the space in between them. It is therefore of great importance to understand plasmas if we want to understand the Universe.

### 3.2 Probe currents

Starting with the simplest system, we consider the situation of a point charge in an ionized gas. Placing a point charge in a plasma will cause particles of the opposite charge to position themselves like a cloud around the point charge. This behavior will shield out the effect of the point charge in the ionized gas. The shielding cloud is called a Debye sheath and it is present around every charged object that is located in a plasma. The characteristic radius of the Debye sheath is called the Debye length and is, for electrons and singly charged ions respectively, given by

$$\lambda_{e,i} = \sqrt{\frac{\epsilon_0 k_B T_{e,i}}{q_e^2 n_{e,i}}}$$  \hspace{1cm} (3)

where $\epsilon_0$ is the electric permittivity of free space, $k_B$ is the Boltzmann constant, $T_{e,i}$ is the plasma electron or ion temperature, $n_{e,i}$ is the plasma electron or ion number density and $q_e$ is the electron charge. The total Debye length $\lambda_D$ is given by

$$\lambda_D^{-2} = \lambda_e^{-2} + \lambda_i^{-2}.$$  \hspace{1cm} (4)
If a body is placed in a plasma it will be hit by the electrons and ions of the plasma, which will charge the body. Introducing the simplest scenario, when the body is only affected by the electrons and ions of the surrounding plasma, the body will build up a negative charge, see Figure 3. The reason for this is that the frequency of hits from electrons is larger than the one from ions, because electrons, due to their much lower mass, move much faster than ions of the same temperature. If the body is a conductor, the charging will cause a current to run through the conductor. The negative charge will be built up until the conductor reaches a potential where the electron current $I_e$ and the ion current $I_i$ are equal so there is no net current, $\sum I = I_e + I_i = 0$ (Høymork, 2000). In connection with a spacecraft this potential is called the spacecraft potential.

![Figure 3](image)

Figure 3: A body in a plasma of electrons and ions will be negatively charged since the electrons will hit the body more frequently, due to their larger velocity. The negative charge will start to attract ions and repel electrons. Eventually an equilibrium will be reached. Picture from the IRF webpage (IRF, 2012).

The Langmuir probe is a conductor and when located in a plasma the description above is applicable. By measuring the generated current the amount of attracted particles can be estimated. A larger current corresponds to a higher flux of particles and thereby the density of the plasma can be determined. The velocities of the particles in a plasma are described by a distribution function $f$. We assume Maxwell-Boltzmann (normal) distribution.
\[ f = n_\infty \left( \frac{m}{2\pi k_B T} \right)^{3/2} \exp \left( -\frac{1}{2} \frac{m}{k_B T} \left( v_x^2 + v_y^2 + v_z^2 + q\varphi \right) \right), \]  

(5)

where \( n_\infty \) is the unperturbed number density far from the probe, \( m \) is the particle mass, \( k_B \) is the Boltzmann constant, \( T \) is the particle temperature, \( v_x, v_y, \) and \( v_z \) are the velocities in \( x, y, \) and \( z \) direction, \( q \) is the particle charge and \( \varphi \) is the potential (Laframboise and Parker, 1973). The flux to the probe is given by integrating the distribution function \( f \) times the velocity in the direction normal to the probe surface (Laframboise and Parker, 1973). For an isotropic distribution, like Maxwell-Boltzmann, it does not matter which component we chose, so we can arbitrarily select \( v_x \).

Using spherical coordinates we get

\[
J = \int f v_x d^3v = n_\infty \left( \frac{m}{2\pi k_B T} \right)^{3/2} \exp \left( -\frac{q\varphi}{k_B T} \right) \int_{v=\infty}^{v=\infty} \int_{\theta=\pi/2}^{\theta=0} \int_{\psi=0}^{\psi=2\pi} \exp \left( -\frac{mv^2}{2k_B T} \right) v^2 \sin\theta dv d\theta d\psi = n_\infty \left( \frac{m}{2\pi k_B T} \right)^{3/2} \exp \left( -\frac{q\varphi}{k_B T} \right) \frac{\pi}{2} \left( \frac{2\pi k_B T m}{\pi} \right) \left( 1 - \frac{q\varphi}{k_B T} \right) = J_0 \left( 1 + \chi \right) \]

(6)

where \( J_0 = n_\infty \left( k_B T/2\pi m \right)^{1/2} \) is the random flux and \( \chi = -q\varphi/k_B T \) (Laframboise and Parker, 1973). The current to the probe is obtained by

\[ I = JqA_{LP} \]

(7)

where \( A_{LP} = 4\pi r_{LP}^2 \) is the probe surface and \( r_{LP} \) is the Langmuir probe radius.

The theory behind the Langmuir probe was first presented in the 1920’s by Mott-Smith and Langmuir. They used Orbital Motion Limited (OML) theory (Mott-Smith and Langmuir, 1926). OML theory considers particle orbits within the sheath around the conductor, assuming the screening effect of the Debye sheath is small and the motion of individual particles is independent of other particles’ motions (Mott-Smith and Langmuir, 1926). This is fulfilled when \( r_{LP} \ll \lambda_D \), \( r_{LP} \) being the probe radius and \( \lambda_D \) the Debye length (Mott-Smith and Langmuir, 1926). Within OML theory the particle trajectories are determined by the conservation of energy and angular momentum (Mott-Smith and Langmuir, 1926). For the situation of a strong sheath effecting the orbits of the particles the Sheath Limited (SL)
theory is used. SL theory is used when $r_{LP} \gg \lambda_D$ and the screening effect is significant (Høymork, 2000). This situation only occurs in really dense plasmas, like, e.g., inside the ionosphere of a celestial body. Since this report will not involve events in very dense plasmas the SL theory is not further described.

For a probe located in a space plasma, such as for example the Saturnian magnetosphere, the dominant current contributors are usually the ion, electron and photoelectron current, $\sum I = I_e + I_i + I_{ph}$. The photoelectron current is due to electrons being emitted from the probe due to the solar EUV radiation, as will be discussed further in Section 3.3. Different voltages set to the probe would result in different currents measured. The voltage-current characteristic for a Langmuir probe would, according to theory, look like the graph of Figure 4. Here the ion current $I_i$ on the negative voltage side and the electron current $I_e$ for the positive voltage side are given by Equation 7 for the ions and electrons respectively. For the ion current we

Figure 4: A theoretical voltage-current characteristic for a Langmuir probe, with the S/C potential measured at the probe ($U_1$) equal to zero. The dashed line represents the electron current $I_e$, the dash-dotted line represents the ion current $I_i$, the dotted line represents the photoelectron current $I_{ph}$, and the solid line is the sum of these currents, the total current $I_{tot} = I_e + I_i + I_{ph}$.
where $q_i$ is the ion charge, $m_i$ is the ion mass, the potential $\phi = U_1 + U_{bias}$, $U_{bias}$ is the bias voltage to the probe and $U_1$ is the S/C potential measured at the probe (also referred to as the floating potential). For the electron current on the positive voltage side we use

$$I_e = I_{e0}(1 - \chi_e)$$

where

$$I_{e0} = -A_{LP} n_e q_e \sqrt{\frac{k_B T_e}{2\pi m_e}}$$

and

$$\chi_e = \frac{q_e(U_1 + U_{bias})}{k_B T_e}.$$

For the ion current present on the positive voltage side, and the electron current present on the negative voltage side, the decrease is exponential. The ion current of the positive voltage side is given by

$$I_i = I_{i0} e^{-\chi_i}$$

where $I_{i0}$ is given by Equation 9 and $\chi_i$ by Equation 10. The electron current of the negative voltage side is given by

$$I_e = I_{e0} e^{-\chi_e}$$

where $I_{e0}$ is given by Equation 12 and $\chi_e$ by Equation 13. Equation 8 to
15 are given by Høymork (2000).

Equations 8 to 15 are indeed useful to describe the electron and ion currents to a Langmuir probe, but for some real case scenarios they are too limited. For instance, a relative velocity between the probe and the plasma, which is the usual case for a probe on an orbiting spacecraft, does have an effect on the collected current which is not described by the Equations 8 to 15. When using the OML approach the equations for the electron and ion currents including the relative drift velocity are very intricate. For the ion current an approximation with the same appearance as Equation 8, but with an additional component in comparison to Equation 9 and 10, can be used. The ion current is then given by

\[
I_{i0} \approx -A_{LP}n_i q_i \sqrt{\frac{k_B T_i}{2\pi m_i}} + \frac{v_i^2}{16}
\]

and

\[
\chi_i = \frac{q_i(U_1 + U_{bias})}{m_i v_i^2} + k_B T_i
\]

where \(v_i\) is the ion speed relative to the collector (Fahleson, 1967).

3.3 The photoelectron current

Another significant current contributor for a sunlit Langmuir probe with negative potential located in a space plasma is, in most cases, the photoelectron current \(I_{ph}\). The ion current \(I_i\) and the electron current \(I_e\) are the currents caused by the particles that the plasma consists of, but the photoelectron current \(I_{ph}\) is the current caused by electrons emitted from the probe itself. Those electrons are being knocked out by photons from the Sun hitting the probe, see Figure 5. This process happens when an electron within the probe absorbs the energy of a photon and if the energy is larger than the binding energy of the electron it will be ejected. There is no physical difference between photoelectrons and other electrons; the reason for the different name is only to specify the origin of the photoelectrons.
If the potential of the Langmuir probe is positive the electrons will be emitted and then, depending on the energy of the electron, they may be collected again. The electrons that do manage to escape are causing a small and exponentially decreasing current given by

$$I_{ph} = I_{ph0} e^{-\frac{q_e (U_1 + U_{bias})}{k_B T_{ph}}}$$  \hspace{1cm} (18)

where $I_{ph0}$ is the saturated photoelectron current and $T_{ph}$ is the photoelectron temperature (Grard, 1973). If the probe has a negative potential all the photoelectrons will be emitted from the probe, causing the photoelectron current to be saturated to a constant level $I_{ph0}$. This level depends on the solar EUV spectrum and is given by

$$I_{ph0} = A q_e \int_0^{\lambda_t} \Phi_{\lambda} Y_{\lambda} d\lambda$$  \hspace{1cm} (19)

where $A$ is the area of the sunlit probe surface, $\lambda_t$ is the threshold wavelength for emission, $\Phi_{\lambda}$ is the solar flux and $Y_{\lambda}$ is the photoelectron yield as a function of wavelength (Brace et al., 1988). The yield of the material describes the probability for an electron to be emitted for a certain wavelength. Many materials have been investigated in laboratory in order to find their photoelectron yield (Feuerbacher and Fitton, 1972). Grard (1973) used the laboratory results together with solar flux data to derive photoelectron characteristics. The study showed that typical values of the saturated photoelectron current density ranges from 4 $\mu$A/m$^2$ for graphite to 42 $\mu$A/m$^2$.
for aluminum oxide, at Earth’s orbit. However, actual probes made of the tested materials and flown in orbit around Earth, showed photoelectron current values considerably higher than the laboratory values (Pedersen, 1995). A probable explanation is gas contamination on the probe surface that occurred in the pre-launch environment (Pedersen, 1995). The measured photoelectron current $I_{ph}$ from the Cassini LP showed another unexpected behavior; it varied with the spacecraft attitude. A possible explanation is surface inhomogeneities. It has also been suggested that it could be due to a leakage current from the stub to the probe (Jacobsen et al., 2008). The spherical probe receives the same amount of sunlight independent of the spacecraft attitude, as long as it is not shadowed, and should therefore not show an attitude dependence. However, the stub may be shaded by the probe, as illustrated in Figure 6, and the amount of sunlight received by the stub will then vary with the spacecraft attitude.

Figure 6: The probe-stub configuration. Showing how the probe may shade the stub. Picture from the article “Cassini Langmuir Probe Measurements in the Inner Magnetosphere of Saturn” by Jacobsen et al. (2008).

The magnitude of the measured photoelectron current $I_{ph}$ of the probe depends on five different parameters: the distance to the Sun, the size of the sunlit area, the surface properties of the sunlit area, the solar activity and, in some sense, also on the conditions of the local plasma (Engwall, 2006). The distance to the Sun is important since the intensity of the solar radiation decreases as $1/r^2$ and less photons means less current, which also is the reason why the solar activity level is essential. The area of the sunlit surface and its surface properties are important since this is where the electrons are emitted from. A larger area emits more electrons and a smaller one emits less. The surface properties are important since different materials have different electron binding energy. The measured photoelectron current $I_{ph}$ may also appear to depend on the conditions of the local plasma. This is because in a dense plasma with trapped highly energetic particles these
particles may knock out electrons from the probe inducing a current similar, in every way, to a photoelectron current. This current is actually not a photoelectron current but a secondary electron current, but it may, for some cases, be hard to differ from a photoelectron current. (This section is adapted from Holmberg (2010).)

The photons also affect the spacecraft itself. Many photoelectrons are ejected from the spacecraft surface and together they produce a local plasma cloud around the spacecraft body. This photoelectron cloud is detected as a second electron population by the probe and sometimes the cloud can make it difficult to detect the ambient plasma (Gurnett et al., 2004). The spacecraft photoelectron cloud is also one of the reasons why the Langmuir probe is mounted on a boom, to reduce the effect of the cloud. The secondary electron current that the probe measures due to the cloud is illustrated as the continuous green line of Figure 7, which shows part of the result of a voltage sweep where all the different currents are marked with different colors. Shown in Figure 7 is the ion current $I_i$ (red dashed-dotted line), the photoelectron current $I_{ph}$ (black dashed line), and the currents from three different electron populations (green lines). These electron populations are the photoelectrons from the spacecraft (continuous line) and two electron populations in the ambient plasma with different temperatures. The theoretical current $I_{tot}$, the sum of all the currents described by the equations in Section 3.2, is shown in red and is fitted to the RPWS Langmuir probe data, the blue dots. While electron currents of 100 nA are measured, the ion and photoelectron current are of the order of 0.5 to 1 nA. (This section is adapted from Holmberg (2010).)

The S/C body will not only affect the probe current by adding extra electrons, it can also give rise to a wake effect that will disturb the plasma measurements. In a supersonic plasma flow (i.e. where the kinetic energy of the ions exceeds their thermal energy), the S/C body will act as an obstacle and a wake will be formed behind the S/C. If the plasma is subsonic w.r.t. the electrons, as is almost always the case, they will fill the wake and make it negatively charged (Engwall, 2006).

3.4 Perturbations

The presence of the spacecraft body perturbs Langmuir probe measurements in several ways. This happens in at least five different ways: (1) the spacecraft creates an electric potential disturbance which may extend to
Figure 7: Result of a voltage sweep of the Langmuir probe on Cassini, the graph is reduced to range from -32 V to 10 V (instead of -32 V to 32 V) in order to put focus on the ion current. The ion current $I_i$ is the red dashed-dotted line, the photoelectron $I_{ph}$ is the black dashed line and currents from three different electron populations are shown in green. These electron currents are produced by the photoelectrons from the S/C $I_{e,S/C}$, the continuous line, and two electron populations in the ambient plasma with different temperatures. The theoretical current is shown in red and is fitted to the RPWS Langmuir probe data, the blue dots. Picture adapted from "Ion densities and velocities in the inner plasma torus of Saturn" by Holmberg et al. (2012).

the location of the probe; (2) charged particles will be absorbed by the spacecraft or deflected by its electric field, this can produce number density and flux disturbances near the probe; (3) if the area of the spacecraft body is not large enough, in relation to the probe, the spacecraft potential may change appreciably as the potential of the probe is swept relative to it; (4) photoemission and/or; (5) secondary electrons, from the spacecraft and/or the probe can produce density and potential disturbances near the location of the probe and give extra currents to the probe (Laframboise and Godard, 1974). Perturbation (1) can be divided into two distinct phenomena: (1.1) perturbation of the symmetry of the probe sheath potential and; (1.2) formation of a potential barrier around the probe (Laframboise and Godard,
Perturbation (1) is illustrated in Figure 8. Theory presented by Laframboise and Parker (1973) showed that small asymmetries in the electric potential profile near a probe, perturbation (1.1), is of minor importance for the OML current collection. The potential barrier $U_M$ keeps electrons of the lowest energies from reaching the probe and the measured electron current will be reduced. The barrier depends on the probe radius $r_{LP}$ so a probe with a small radius, 0.25 mm, may be unable to collect a large part of the ambient electrons (Olson et al., 2010). Investigating the probe and spacecraft configuration on Cassini showed the potential barrier to be small, of around 0.35 V, for $U_{bias} = 30$ V and a standard case of Cassini parameters (Olson et al., 2010). However, there might exists a transition region which will disturb electron current measurements (Olson et al., 2010).

![Figure 8: Left panel: Potential profile for a probe and spacecraft where the probe potential has the same sign as that of the spacecraft. Potential disturbances from the probe stem is not shown. The pictures is taken from the article "Perturbation of an Electrostatic Probe by a Spacecraft at Small Speed Ratios" by Laframboise and Godard (1974). Right panel: Potential profile for a negative spacecraft potential $U_{SC}$ and a positive probe potential $U_{LP}$. $U_{pl}$ is the ambient plasma potential, $r_{SC}$ is the spacecraft radius, $l_{boom}$ is the length of the probe boom, $r_{LP}$ is the probe radius, $U_1$ is the potential at the probe position without the contribution from the probe potential, and $U_M$ is a minimum potential which acts as a potential barrier. Picture from "On the Interpretation of Langmuir Probe Data inside a Spacecraft Sheath" by Olson et al. (2010)]](image)

Investigations of perturbation (3) showed that the area difference $A_{S/C}/A_{LP}$ needs to be at least 1000 to avoid a shift in the spacecraft potential when
a bias voltage $U_{\text{bias}}$ is applied (Szuszczewicz, 1990). The dimensions of the Cassini spacecraft, 6.7 m high and 4 m wide, gives an area difference of $\sim$14,000 to the small, 5 cm in diameter, Langmuir probe. This rough calculation shows that a shifting spacecraft potential due to the applied bias voltage should not be a problem for the Cassini spacecraft.

Other causes of perturbations are also present, such as: (6) probe surface contaminations. Perturbation (6), contaminations of the probe surface, can manifest themselves as an hysteresis effect in the sweep. Since the probe sweeps from -32 V to 32 V and then back to -32 V in less than 0.5 s the "upward" and "downward" sweeps are expected to be more or less identical due to the short time scale. If they are not this may be due to contamination. Investigations of contaminated probes have shown that they overestimates the temperature of the electron distribution (Szuszczewicz, 1990). To avoid surface contaminations on the Cassini LP, the probe is cleaned regularly, once per orbit, by applying -100 V for a few hours and letting attracted ions sputter the probe surface clean.
4 The magnetosphere of Saturn

Saturn is the second largest planet in our Solar System and it is located at around 9.6 AU from the Sun. Saturn is known for its magnificent ring system, but it also possesses a magnificent magnetosphere. The magnetic field of Saturn is a dipole-like field created by magnetohydrodynamic processes in the conducting core and the equatorial surface field strength is around $21 \mu T$. The dipole axis is almost aligned with the rotation axis, differing only with less than 1 degree. The magnetic field of the planet acts as a protection against the solar wind and their interaction builds up the planet’s magnetosphere, see Figure 9. The solar wind consists of mainly electrons, hydrogen ions, and helium ions and it also carries the interplanetary magnetic

![Diagram of the magnetosphere of Saturn](image)

**Figure 9:** Illustration of the magnetosphere of Saturn. The solar wind brings mainly electrons, hydrogen ions, and helium ions that hits the outer limit of the magnetosphere, the bow shock. In between the bow shock and the magnetopause is the transition region the magnetosheath. Behind the planet pointing away from the Sun is the magnetotail. The moon Titan is one of the plasma sources of Saturn’s magnetosphere. Adapted from figure by ESA/J. Tubbin, Los Alamos National Laboratory.
field (IMF), which is the extended solar magnetic field. The average IMF magnitude at the position of Saturn is about 0.5 nT. The magnetosphere of any planet will act as an obstacle in the way of the solar wind, that is traveling with a speed of 400 km/s at the orbit of Saturn. Since the flow is moving with speeds larger than the speed of sound a shock wave will be formed, the bow shock, marking the boundary between the supersonic flow of the solar wind and the subsonic flow inside of the bow shock. The distance of the bow shock of Saturn varies, in the Saturn-Sun line direction, between 18 and 46 \( R_S \) (where 1 \( R_S \)=60,268 km is the equatorial radius of Saturn) from the center of the planet, with an average distance of 27.7 \( R_S \) (Gombosi et al., 2009). The distance of the bow shock varies with the solar wind dynamic pressure. Inside of the bow shock is the magnetosheath, which is a region where the magnetic field of the planet is irregular and weak due to the interaction with the IMF. The magnetosheath have irregular subsonic plasma flows and particle densities, temperatures, and magnetic fields that are enhanced compared to the solar wind (Rönnmark, 2000). The inner boundary of the magnetosheath is the magnetopause, this is the location where the pressure of Saturn’s magnetic field counterbalance the pressure of the solar wind. The distance of the magnetopause of Saturn, in the Saturn-Sun line direction, varies between 16 and 27 \( R_S \), with an average distance of 22 \( R_S \) (Gombosi et al., 2009). On the nightside of Saturn the magnetosphere extends into the magnetotail, a very different configuration compared to the dayside magnetosphere. In the center of the magnetotail there is a current sheet that keeps the magnetic field at this location to a very low value (Gombosi et al., 2009). Above an below the current sheet, the magnetic field is larger and radially directed, away from the planet on the north side of the sheet and towards the planet on the south side of the sheet (Gombosi et al., 2009). The magnetotail is also a region where down-tail plasma loss through reconnection can occur. This has been detected by both magnetic field measurements (Jackman et al., 2007) and plasma measurements (Hill et al., 2008). Magnetic reconnection is a process where the magnetic topology is changed through new field line connections that causes magnetic energy to be converted into thermal energy or kinetic energy. However, the plasmoid events that have been detected are few and infrequent, suggesting that such large-scale reconnection are relatively rare in the magnetotail of Saturn (Gombosi et al., 2009).

The Saturnian moon Titan is located at around 20 \( R_S \) from the planet, most of the time just inside of the magnetopause. Titan is one of the plasma sources in Saturn’s magnetosphere. The other plasma sources are:
the solar wind, Saturn's ionosphere, the rings and the icy satellites, in particular the moon Enceladus. Most of the plasma is of internal origin, with the primary sources being the rings and the icy satellites (Dougherty et al., 2009). The main ion components in the magnetosphere are $H^+$, $H_2^+$, $O^+$, $OH^+$, and $H_2O^+$, i.e. mainly protons and water group ions, with a surprisingly low amount of nitrogen ions detected. $N^+$ was expected since Titan was expected to be a large source of nitrogen to the magnetosphere. This was due to the fact that the atmosphere of Titan is thick, with a column density about ten times larger than the one of Earth, and consists of over 95% nitrogen (Brown et al., 2009). A likely explanation to this lack of $N^+$ in the outer magnetosphere is the inability of the plasma around Titan to build up substantial densities (Dougherty et al., 2009). The plasma density at the orbit of Titan is only about 0.1 particle/cm$^3$ (Morooka et al., 2009). Even though Titan is not contributing to the magnetosphere with as much $N^+$ as was previously expected it is still an important plasma source. The estimated escape rates of hydrogen from Titan’s atmosphere to the surrounding magnetosphere are large, around $1-3 \times 10^{28}$ amu/s (Brown et al., 2009). Also the escape rates of methane by precipitation as hydrocarbons are large, of around $10-30 \times 10^{28}$ amu/s (Brown et al., 2009). Titan have no internal magnetic field, this makes the study of Titan’s interaction with Saturn’s magnetosphere particularly interesting since it is the only known case in our Solar System where an unmagnetized body with a thick atmosphere interacts with the plasma in a magnetosphere.

The Cassini spacecraft has to a very large degree contributed to our understanding of the magnetosphere of Saturn. Some of the most important findings are: the plumes of the moon Enceladus, Cassini could show that the moon Enceladus is feeding the inner magnetosphere with new material trough water vapor plumes located close to its southern pole; that the inner rings have there own ionosphere; very few nitrogen ions; a new radiation belt inside of the D ring; the presence of very heavy negatively charged particles in the homopause of Titan (Dougherty et al., 2009). These and many other discoveries would not have been possible without the in-situ measurements of Cassini. And Cassini is still to the date of writing providing us with a better and better understanding of Saturn and its surrounding.

4.1 The inner magnetosphere of Saturn

The region that is investigated for this study is the inner magnetosphere of Saturn, from the end of the main rings at $2.5 \ R_S$ out to around $12 \ R_S$. 
This region contains the moons Mimas (3.07 R$_S$), Enceladus (3.95 R$_S$), Tethys (4.88 R$_S$), Dione (6.25 R$_S$), and Rhea (8.73 R$_S$), see Figure 10. Enceladus is the most prominent of them, since it is constantly feeding the inner magnetosphere with new materials through water vapor plumes coming from ridges and troughs located in its south polar region, see Figure 11. These water vapor jets create a torus around Saturn at the orbit of Enceladus that is called the Enceladus torus, see Figure 10.

Figure 10: Illustration of the inner magnetosphere of Saturn. Shown are the relative positions of the moons Mimas (3.07 R$_S$), Enceladus (3.95 R$_S$), Tethys (4.88 R$_S$), Dione (6.25 R$_S$), and Rhea (8.73 R$_S$). Around the moon Enceladus is the Enceladus torus, created by materials expelled from the interior of Enceladus. The Enceladus torus material is scattered and dissociated and creates the E-ring torus. Local interchange instabilities create cold and dense plasma to move outwards and hot and tenuous plasma to move inwards. Picture from”Mapping Magnetospheric Equatorial Regions at Saturn from Cassini Prime Mission Observations” by Arridge et al. (2011).

The Enceladus torus is a torus of mainly neutrals, with densities of around
$10^4 \text{cm}^{-3}$. The main neutral species are O, OH and H$_2$O. The neutral torus is scattered by charge exchange, ion/neutral scattering, molecular dissociation, and neutral/neutral scattering (Cassidy and Johnson, 2010).

Enceladus is also a very prominent plasma source with a production rate of around $\sim$300 kg/s (Gombosi et al., 2009). Cassini has found that the dominant ion species of the inner magnetosphere are hydrogen ions H$^+$ and water group ions W$^+$ (O$^+$, OH$^+$, H$_2$O$^+$, and H$_3$O$^+$) (Gombosi et al., 2009). The plasma temperatures are $\sim$2 eV at 3.5 RS and are steadily increasing to $\sim$10 eV at 8 RS for hydrogen ions and electrons (Gombosi et al., 2009). The temperatures for water group ions start at $\sim$40 eV and increases up to $\sim$100 eV, for the same radial interval (Sittler et al., 2005). However, these temperatures have been estimated to lower values by e.g. Thomsen et al. (2010), showing 30 eV at 6 RS, and Wahlund et al. (2005) showing up to 8 eV at 4 RS. At the position of Enceladus the centrifugal force acting on the plasma is much larger than the gravitational force so the only way to confine the plasma is by magnetic forces (Dougherty et al., 2009). Due to the centrifugal force most of the plasma is confined to the equatorial region. The magnetosphere of Saturn can be divided into three distinct regions, regarding the structure of the magnetic field: within 4 RS it is a strong dipole, between 4 and $\sim$15 RS is a quasi-dipolar region, and beyond 15 RS is a region with stretched magnetic field lines at dawn (Arridge et al., 2007).
4.2 Investigation of the inner plasma torus

For our investigations of the inner magnetosphere of Saturn we have used plasma data from the Cassini Langmuir probe, recorded during the period from orbit 3 to 133. This time interval corresponds to the 1st of February 2005 to the 27th of June 2010. The results of the investigations are presented in the two papers included in the end of this thesis and are only shortly described here. The results are based on a new method to derive ion plasma parameters from the Langmuir probe. Earlier estimates have not been as accurate due to the lack of measurements of photoelectron current, instead a fixed value has been used, and the overestimation of the ion temperature. A large ion temperature would give a large current contribution and for such a case the presented density and velocity derivation method would not have been possible to use. The first step of the new method is to estimate the measured photoelectron current, this process is described in detail in Holmberg (2010). The basic principle of the method is to use many years of measurements from the outer magnetosphere where the measured current on the negative voltage side is dominated by the photoelectron current and relate the EUV index, measured at Earth as the F10.7 index and converted to an EUV index that would be measured at Saturn, to the measured current. A linear relation is derived with higher EUV index producing a larger current, this relation is then used to derive the photoelectron current at all positions. The measured current is not only due to the photoelectron current $I_{ph}$ and the ion current $I_i$, but can be described with

$$I_{tot} = I_i + I_e + I_{ph} + I_{bse} + I_{se} + I_{si} + I_b$$

where $I_e$ is the electron current, $I_{bse}$ is the current of backscattered electrons due to $I_e$, $I_{se}$ and $I_{si}$ is due to secondary electrons emitted when ions and electron hit the spacecraft, and $I_b$ is the current from a possible ion source on the spacecraft, such as e.g. thrusters (Engwall, 2006). To avoid $I_e$ and $I_{bse}$, only current measurement from below -5 V are used. In sunlit magnetospheric plasmas $I_{se}$ and $I_{si}$ are usually very small compared to $I_{ph}$ (Engwall, 2006), the few cases where this is not the case are of little statistical significance. This is also the case for $I_b$, which will have a small impact on the large data set used in our study. This is one of the advantages of using several years of recorded data instead of choosing a fixed $I_{ph}$ value for each orbit. If using the same value for all orbits the changing activity of the Sun will not be included and the $I_{ph}$ estimation will be less accurate.

The plasma densities of the inner magnetosphere of Saturn have previously
been estimated by e.g. Wahlund et al. (2005), who used Cassini LP data from the Saturn Orbit Insertion (SOI) to estimate electron densities between 2 and 20 Rs. Persoon et al. (2005) derived electron densities using upper hybrid resonance emissions detected by the RPWS instrument, using data from five orbits from the years 2004 and 2005. They derived a power law describing the density behavior in between 5 and 9 Rs. A power law that agrees very well with our estimated ion densities. More recent density estimations also agree well with our estimations, such as the ones by e.g. Thomsen et al. (2010), using Cassini Plasma Spectrometer (CAPS) data, and Persoon et al. (2009), using an extended RPWS data set. These agreements with density estimates from other Cassini instruments gives us a valuable confirmation that our ion density derivation method is valid. Regarding the ion velocity there has not been as many other estimates to compare with, the main one being from the CAPS instrument, see e.g. Wilson et al. (2009) and Thomsen et al. (2010). However, the good agreement of the density estimations implies a similar reliability of our derived ion velocities since they are derived from the same data set. The two main factors that could introduce an error in the estimated ion velocities are the assumption of the ion flow being mainly in the azimuthal direction and a large thermal velocity of the ions. Several studies, e.g. Sittler et al. (2006), Wilson et al. (2008), and Thomsen et al. (2010), have shown that the dominant direction of the ion flow is in the azimuthal direction, so it seems to be a valid assumption. In Paper I we estimate the effect of the thermal component of the ion current using the ion temperatures presented by Sittler et al. (2006) and Thomsen et al. (2010) and show that the overestimation should be just a few km/s and therefore only have a minor effect on the result.

One of the main results of Paper I was an indication of a very dynamic plasma torus. For each radial distance the estimated densities where in a wide range, at the orbit of Tethys (4.88 Rs) we measure densities from 20 cm$^{-3}$ to 110 cm$^{-3}$, a range of 90 cm$^{-3}$, the expected range caused by the errors of the derivation method would be 20 cm$^{-3}$. So this wide range of measured densities where interpreted as caused by spatial or temporal variations of the plasma torus. The wide range was also seen in the estimated velocities. This was the motivation for the work presented in Paper II. Recently, many studies have been presented showing day/night side asymmetries in a number of different parameters related to the plasma disk. As we investigated the local time (LT) distribution of the ion density and azimuthal velocity we also found a day/nigh asymmetry. The densities ranges from
an average of $\sim 35 \text{ cm}^{-3}$ for the lowest dayside values close to noon up to $\sim 70 \text{ cm}^{-3}$ for the highest nightside values around midnight. This can be explained by the additional ion velocity component also detected with the LP and by the CAPS instrument. Wilson et al. (2013) presented measurements of the radial ion velocity $v_r$, showing higher velocities for the dawn and dusk components than the noon and midnight components. The measured velocity difference $\Delta v_{i,r} \sim 3-10 \text{ km/s}$. With the LP we measure the azimuthal ion velocity component which shows a similar asymmetry but with a difference $\Delta v_{i,\theta} \sim 5-10 \text{ km/s}$. These differences in ion velocity for different LT will cause the plasma to move outwards from Saturn as it moves from the nightside to the dayside, and the plasma will be more scattered on the dayside. This can be seen as lower ion densities detected on the dayside than on the nightside of Saturn, for a chosen radial distance. Apart from presenting the measurements, Paper II also suggests that the cause of the asymmetry could be radiation pressure acting on negatively charged dust located in the E-ring. But the presented model needs to be further investigated, preferably as a hybrid simulation with the dust included as a plasma component.

There are also other spatial variations that could explain the wide range in the measured ion density. One is that the ion density could be varying with Saturn Longitude System (SLS). Since Saturn is a gas giant with no detectable solid surface it is hard to define a longitude system, so other sources than visual detection needs to be used. SLS is a longitude system based on radio emissions at kilometer wavelengths emitted from Saturn’s polar regions. This radiation is called Saturn Kilometric Radiation (SKR) and was previously thought to represent the rotation period of the planet. It is now know that the radiation from the north and the south pole have two different periods and that they both vary with time. This make it extra difficult to define a longitude system but the SLS is a good approximation for the time interval between 2004 and 2009, when the SKR period for the south component was almost constant. Gurnett et al. (2007) used the SLS to detect an electron density variation. They used electron densities derived from the upper hybrid frequency recorded during 14 Cassini orbits in 2005 and 2006. They found an electron density minimum around longitude 160 degrees and a maximum around 340 degrees in the radial region 3 to 5 $R_S$. They suggested this region to be the source region of the prominent SKR dependence detected in the outer magnetosphere of Saturn by e.g., Clarke et al. (2006); Morooka et al. (2009). Also the LP ion density showed an SLS dependence for the same time period and radial region used by Gurnett et al. (2007). However, the data showed a strong radial dependence,
lower densities detected further away from the radial distance of Enceladus (the plasma source) and higher densities detected closer to the Enceladus orbit. Compensating for the radial dependence reduced some of the clear SLS dependence that was first detected. Also, using an extended data set, beyond year 2006, did not show the same SLS variability in the data. This could be due to the difficulty of using SKR to define a longitude system since it is varying with time and choice of component (south or north). Overall, a possible SLS variability in the plasma of the region 3 to 5 Rs could not be confirmed (nor disproved) using the LP ion density. However, ion density measurements from a few orbits does not follow the detected day/night side asymmetry, but instead show lower densities for the nightside and higher densities for the dayside. This indicates that there is an additional process causing density variations in the inner plasma torus, that could be the SLS dependence suggested by Gurnett et al. (2007) or it could be the recently detected time variability of the Enceladus plume (Hedman et al., 2013). All in all, this calls for further investigations of Saturn’s inner plasma torus.
5 Summary of publications

5.1 Paper I: Ion Densities and Velocities in the Inner Plasma Torus of Saturn

Authors: M.K.G. Holmberg, J.-E. Wahlund, M.W. Morooka, and A.M. Persoon

Journal: Planetary and Space Science

Status: Published

In this paper we investigate the structure and the dynamics of the inner plasma torus of Saturn. We use plasma data from the Cassini Radio and Plasma Wave Science (RPWS) Langmuir probe (LP), an instrument which is constructed and operated by the Swedish Institute of Space Physics, to map the ion density and velocity of Saturn’s inner plasma torus. Data recorded during the period from orbit 3 to 133, which corresponds to the 1st of February 2005 to the 27th of June 2010, are used to map the extension of the inner plasma torus. The dominant part of the plasma torus, ion density above \( \sim 15 \) particle/cm\(^3\), is shown to be located in between 2.5 and 8 Saturn radii (1 \( R_S \) = 60,268 km) from the planet, with a north-southward extension of \( \pm 2 R_S \). The derived plasma disk ion density shows a broad maximum in between the orbits of the moons Enceladus and Tethys. Ion density values vary between 20 and 125 cm\(^{-3}\) at the location of the density maximum and since the error of the derivation method is expected to introduce a density range of \( \sim 20 \) cm\(^{-3}\) the additional density range is interpreted as being due to the dynamics of the plasma disk. The equatorial density structure, limited to \(|z| < 0.5 R_S\), shows a slower decrease away from Saturn than towards. The outward decrease, from 5 \( R_S \), is well described by the relation

\[
n_{eq} = 2.2 \times 10^4 (1/R)^{3.63},
\]

a relation first derived for electron densities by Persoon et al. (2005). The plume of the moon Enceladus is clearly visible as an ion density maximum of \( 10^5 \) cm\(^{-3}\), only present at the south side of the ring plane, as expected since the Enceladus plumes are located in the south polar region. A less prominent density peak, of 115 cm\(^{-3}\), is also detected at the orbit of Tethys, at \( \sim 4.9 R_S \), which could be an indication of particle sputtering from or active vents on Tethys. Density peaks are not recorded...
at the location of the orbits of the moons Mimas, Dione, and Rhea. Also the azimuthal ion velocity $v_{i,\theta}$ is estimated, showing a clear general trend in the region between 3 and 7 Rs, described by $v_{i,\theta} = 1.5R^2 - 8.7R + 39$. Outside of this region the measurements are to close to the noise level of the instrument to produce a reliable estimation of $v_{i,\theta}$. The average $v_{i,\theta}$ starts to deviate from corotation speed at around 3 Rs and reaches down to $\sim$68% of corotation close to 5 Rs.

5.2 Paper II: Day/Night Side Asymmetry of Ion Densities and Velocities in Saturn’s Inner Magnetosphere

Authors: M.K.G. Holmberg, J.-E. Wahlund, and M.W. Morooka

Journal: Geophysical Research Letters

Status: Submitted

In this paper we extend our investigation of the inner plasma disk of Saturn. Holmberg et al. (2012) showed that the Cassini Radio and Plasma Wave Science (RPWS) Langmuir probe (LP) measures a great range of the ion density and velocity for any chosen radial distance. This could be explained by the here presented day/night asymmetry detected in both ion density and velocity. We present Cassini LP ion density and velocity measurements from 129 orbits, more than 5 years of data. The data show a clear day/night side asymmetry in both ion density and ion velocity, most prominent in the radial region 4-6 Rs (1 Rs=60,268 km) from the center of Saturn. The ion densities $n_i$ varies from an average of $\sim$35 cm$^{-3}$ for the lowest dayside values close to noon up to $\sim$70 cm$^{-3}$ for the highest nightside values around midnight. The azimuthal ion velocities $v_{i,\theta}$ varies from $\sim$28-32 km/s at the lowest dayside values around noon to $\sim$36-40 km/s at the highest nightside values around midnight. This gives an azimuthal ion velocity difference between noon and midnight of $\Delta v_{i,\theta} \sim$5-10 km/s. Recent measurements have shown that large amount of negatively charged nm-sized dust are ejected from the plumes of Enceladus (Jones et al., 2009; Hill et al., 2012). If the densities of negatively charged nm-sized grains in the rest of the plasma disk also is high this will have a noticeable effect on the dynamics of the plasma disk. The detected
day/night asymmetry is suggested to be due to the radiation pressure force acting on the negatively charged nm-sized dust of the E-ring. This force will introduce an extra grain and ion drift component equivalent to the force of an additional electric field of 0.1-2 mV/m for a 10-50 nm sized grain. The additional drift component can explain the day/night asymmetry of the azimuthal ion velocity. It can also explain the asymmetry of the ion density, since the ions will be pushed outwards in their orbit as they move from the nightside towards the dayside and will therefore be scattered on the dayside.
6 Notation

\( A \) \hspace{1em} \text{area of the sunlit probe surface}
\( A_{LP} \) \hspace{1em} \text{area of the Langmuir probe}
\( A_{S/C} \) \hspace{1em} \text{area of the spacecraft}
\( E_i \) \hspace{1em} \text{ionization energy}
\( f \) \hspace{1em} \text{distribution function}
\( h \) \hspace{1em} \text{Planck constant}
\( I \) \hspace{1em} \text{current}
\( I_b \) \hspace{1em} \text{current due to spacecraft ion source}
\( I_{bse} \) \hspace{1em} \text{current due to backscattered electrons}
\( I_e \) \hspace{1em} \text{electron current}
\( I_i \) \hspace{1em} \text{ion current}
\( I_{ph} \) \hspace{1em} \text{photoelectron current}
\( I_{ph0} \) \hspace{1em} \text{saturated photoelectron current}
\( I_{se} \) \hspace{1em} \text{secondary electron current due to electron hits}
\( I_{si} \) \hspace{1em} \text{secondary electron current due to ion hits}
\( I_{tot} \) \hspace{1em} \text{total current}
\( J \) \hspace{1em} \text{particle flux}
\( J_0 \) \hspace{1em} \text{random particle flux}
\( k_B \) \hspace{1em} \text{Boltzmann constant}
\( m \) \hspace{1em} \text{particle mass}
\( m_e \) \hspace{1em} \text{electron mass}
\( m_i \) \hspace{1em} \text{ion mass}
\( n_e \) \hspace{1em} \text{electron number density}
\( n_i \) \hspace{1em} \text{ion number density}
\( n_n \) \hspace{1em} \text{neutral particle number density}
\( n_\infty \) \hspace{1em} \text{unperturbed number density at infinity}
\( q \) \hspace{1em} \text{particle charge}
\( q_e \) \hspace{1em} \text{electron charge}
\( q_i \) \hspace{1em} \text{ion charge}
\( r \) \hspace{1em} \text{distance}
\( r_{LP} \) \hspace{1em} \text{Langmuir probe radius}
\( T \) \hspace{1em} \text{particle temperature}
\( T_e \) \hspace{1em} \text{electron temperature}
\( T_i \) \hspace{1em} \text{ion temperature}
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<thead>
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<tr>
<td>$U_1$</td>
<td>S/C potential</td>
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<tr>
<td>$U_{bias}$</td>
<td>bias voltage</td>
</tr>
<tr>
<td>$v_i$</td>
<td>ion speed relative to the collector</td>
</tr>
<tr>
<td>$v_x$, $v_y$, and $v_z$</td>
<td>velocities in $x$, $y$, and $z$-direction</td>
</tr>
<tr>
<td>$Y_\lambda$</td>
<td>photoelectron yield as a function of wavelength</td>
</tr>
<tr>
<td>$\epsilon_0$</td>
<td>electric permittivity of free space</td>
</tr>
<tr>
<td>$\lambda_D$</td>
<td>total Debye length</td>
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<td>$\lambda_e$</td>
<td>electron Debye length</td>
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<tr>
<td>$\lambda_i$</td>
<td>ion Debye length</td>
</tr>
<tr>
<td>$\lambda_t$</td>
<td>threshold wavelength for photoelectron emission</td>
</tr>
<tr>
<td>$\varphi$</td>
<td>electric potential</td>
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<tr>
<td>$\Phi_\lambda$</td>
<td>solar flux</td>
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References


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Ion densities and velocities in the inner plasma torus of Saturn

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Cassini

A B S T R A C T

We present plasma data from the Cassini Radio and Plasma Wave Science (RPWS) Langmuir probe (LP), mapping the ion density and velocity of Saturn’s inner plasma torus. Data from 129 orbits, recorded during the period from the 1st of February 2005 to the 27th of June 2010, are used to map the extension of the inner plasma torus. The dominant part of the plasma torus is shown to be located in between 2.5 and 8 Saturn radii (1 Rs ≈ 60,268 km) from the planet, with a north-southward extension of ± 2 Rs. The plasma disk ion density shows a broad maximum in between the orbits of Enceladus and Tethys. Ion density values vary between 20 and 125 cm−3 at the location of the density maximum, indicating considerable dynamics of the plasma disk. The equatorial density structure, |z| < 0.5 Rs, shows a slower decrease away from the planet than towards. The outward decrease, from 5 Rs, is well described by the relation \( n_i = 2.2 \times 10^4 (1/R_s)^{1/3} \). The plume of the moon Enceladus is clearly visible as an ion density maximum of 10^5 cm−3, only present at the south side of the ring plane. A less prominent density peak, of 115 cm−3, is also detected at the orbit of Tethys, at \( \sim 4.9 \) Rs. No density peaks are recorded at the orbits of the moons Mimas, Dione, and Rhea. The presented ion velocity \( v_{i,b} \) shows a clear general trend in the region between 3 and 7 Rs, described by \( v_{i,b} = 1.5R_s^{2} – 8.7R_s + 39 \). The average \( v_{i,b} \) starts to deviate from corotation at around 3 Rs, reaching \( \sim 68\% \) of corotation close to 5 Rs.

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1. Introduction

Most of what was known about the plasma of Saturn’s inner magnetosphere before the Cassini mission was based on measurements by the plasma instruments on Pioneer 11 and Voyager 1 and 2. The three spacecraft passed by Saturn in 1979, 1980, and 1981, respectively, on their way further out in the Solar System. A much larger data set has been provided by the Cassini spacecraft, which went into orbit around Saturn on July 1, 2004. Cassini observations have, among many other discoveries, revealed that the moon Enceladus expels water vapor and condensed water from ridges and troughs located in its south polar region (Dougherty et al., 2006; Porco et al., 2006). These plumes or jets of water create a narrow neutral water vapor cloud extending all around Saturn along the orbit of Enceladus. This narrow neutral torus is related (Johnson et al., 2006) to the larger OH torus observed by the Hubble Space Telescope (Shemansky et al., 1993). Photoionization and impact ionization of the water molecules, and subsequent transport, create a plasma torus around Saturn at the position of the neutral torus. The first orbit of Cassini, the Saturn orbit injection, provided data for many estimates of the properties of the inner plasma torus, such as density and temperature (e.g., Moncuquet et al., 2005; Wahlund et al., 2005; Sittler et al., 2006). The gradually larger data sets provided further conclusions on the nature of the plasma torus; such as the investigation of the electron density, showing a highly repeatable radial dependence beyond 5 Rs, consistent with a centrifugally driven outward plasma flow (Persoon et al., 2005). The dynamics of the inner plasma torus have also been investigated by Garnett et al. (2007), who suggested a two-cell convection pattern to be the cause of the recorded electron density variation. The ion flow velocities of the inner plasma torus were investigated using Cassini Plasma Spectrometer (CAPS) data, showing subcorotation (\(~ 75\%\)) beyond 3 Rs (Wilson et al., 2009). A similar result (\(~ 50–70\%\) of corotation speed) was shown with an extended CAPS data set, using roughly 4.5 years of CAPS data (Thomsen et al., 2010).

Here we present ion density \( n_i \) and velocity \( v_i \) results from the Radio and Plasma Wave Science (RPWS) Langmuir probe (LP), showing the structure and rotation speed of the plasma torus. The measurements are from 129 orbits, with good coverage, which gives a good statistical foundation for the presented, and future, studies. In Section 2 we present the RPWS LP experiment method and the theoretical basis for the derived ion densities \( n_i \) and velocities \( v_i \). The observations and the error sources are presented in Section 3. The interpretation of the results and comparisons with other studies are presented in Section 4 and the conclusions are given in Section 5.
2. RPWS LP experiment methods

A full description of the RPWS instruments is given by Gurnett et al. (2004), with further details of the LP measurement methods provided by Morooka et al. (2011) and Wahlund et al. (2009). The RPWS LP consists of a titanium sphere, 5 cm in diameter, with a titanium nitride coating. The sphere is mounted at the end of a 0.8 m long boom, which folds out from a tripod mounting, giving the sphere an approximate distance of 1.5 m to the nearest spacecraft surface. To minimize disturbances the 10.9 cm of the boom closes to the sphere has a diameter of only 6.35 mm and is held at the same potential as the sphere. This part, the so-called stub, is also made of titanium with a titanium nitride coating. The probe-stub configuration, also showing how the probe may shade the spacecraft surface. To minimize disturbances the 10.9 cm of the stub, is also made of titanium with a titanium nitride coating. This part, the so-called stub, is also made of titanium with a titanium nitride coating. The sphere is mounted at the end of a 10.9 cm of the probe itself.

Fig. 1. The probe-stub configuration, also showing how the probe may shade the spacecraft attitude dependence in the measured current, further referred to the web version of this article.)

The measured data points are fitted to a current–voltage (I–V) curve using the Orbital Motion Limited (OML) theory (Mott-Smith and Langmuir, 1926). The theory for the case of a drifting Maxwellian plasma has been developed by e.g., Medicus (1961). A numerically convenient approximation for the sampled ion current was provided by Fahlsten (1967) as

\[ I_i \approx I_{i0} \left( 1 - \frac{q_i(U_i + U_{bias})}{m_i v_i^2} \right) \left( 1 + \frac{k_B T_i}{2 m_i} \right) \]

where

\[ I_{i0} = -A_{LP} n_i q_i \sqrt{\frac{v_i^2}{16} + \frac{k_B T_i}{2 \pi m_i}} \]

is the random current, \( A_{LP} \) is the surface area of the Langmuir probe, \( U_i \) is the spacecraft potential measured at the probe (also referred to as the floating potential), \( U_{bias} \) is the bias voltage of the probe, \( k_B \) is the Boltzmann constant, and \( q_i/T_i(n_i/v_i)/m_i \) are the charge/temperature/density/drift velocity/mass of the ith ion species. The floating potential \( U_1 \) is given by the potential shift from 0 V, clearly visible in the derivative of the sweep, see for instance Fig. 1 (panel c) in Gustafsson and Wahlund (2010). An example of a sweep is shown in Fig. 2, showing data for \( U_{bias} < 10 \) V. For this study we only focus on the ion signal, i.e. \( U_{bias} < 0 \) V, and to make sure no significant electron contribution is present in our data we chose an even stronger condition, \( U_{bias} < -5 \) V, for the data used. Fig. 2 shows the fit \( I_\perp \) (red line) to the measurements (blue dots) which is given by the ion current \( I_i \) (red dashed-dotted line) and the photoelectron current \( I_{ph} \) (black dashed line). The photoelectron current is due to the photoelectric effect where the absorption of photons by the probe causes electrons to be emitted from the probe itself.

During the short timescale of one sweep the plasma parameters of Eqs. (1) and (2), as well as \( U_i \) and \( I_{ph} \), are observed to be constant. This is concluded since the sweeps are performed from \(-32 \) V to \(32 \) V and back to \(-32 \) V without any significant hysteresis effect. The ion data also shows a clear linear trend, with a spread, the noise level, of 0.1 nA. This gives us the possibility to express the total measured current \( I_\perp = I_i + I_{ph} \), in the region \( U_{bias} < -5 \) V, as a linear function. Setting

\[ m = I_{i0} \left( 1 + \frac{q_i U_i}{m_i v_i^2} + k_B T_i \right) + I_{ph} \]

and

\[ b = -m \frac{q_i I_{i0}}{m_i v_i} \left( 1 + k_B T_i \right) \]

we obtain

\[ I_\perp = m + b U_{bias} \]

where \( b \) is the slope of our fit and \( m \) is the \( I_\perp \)-value for \( U_{bias} = 0 \) V. The \( m \)-value is used to represent the \( I_\perp \)-current for each sweep. Plotting \(-m \) reveals that the LP measurements on the negative voltage side are dependent on the spacecraft attitude (Fig. A1). This dependence is corrected for using the method described in Appendix A.

We estimate the magnitude of the photoelectron current \( I_{ph} \), using the method described in Appendix B, and subtract it from the \( m \)-values given by our fit to the sweep data. The estimated photoelectron current \( I_{ph} \) is correct within \( \pm 0.1 \) nA (instrument noise level). The LP estimates the total energy (thermal + ram), so we need to consider both the thermal and the ram motion. However, the upper

Fig. 2. The current–voltage characteristics of a voltage sweep from orbit 11. The RPWS LP data (blue dots) are fitted by the theoretical current \( I_\perp \) (red line), which is given by the ion current \( I_i \) (red dashed-dotted line) and the photoelectron current \( I_{ph} \) (black dashed line). A small contribution from the electron current \( I_e \) (green line) is also present on the negative voltage side. This contribution is avoided by only using data taken for \( U_{bias} < -5 \) V, i.e. data from the shaded region is not included in our analysis. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)
limit of the ion temperature $T_i$ near 4 RS has been derived, using three orbits, to 1–8 eV (Wahlund et al., 2009). Such low temperatures give a very small contribution to the total current. However, at larger distances from the planet the temperature increases and could have an effect on the measurements. The consequences of higher temperatures on our derived ion drift speeds is further discussed in the last part of Section 4. Using Eqs. (3) and (4), and neglecting the thermal component gives

$$m - I_{ph} = I_0 \left( 1 - \frac{q_i U_i}{m_i v_i^2} \right) = I_0 + b U_0. \tag{6}$$

The parameters $m$ and $b$ are derived from our data fit and using $U_0$, which is the potential value for $I = 0$ nA, as a proxy for $U_i$. We can derive $I_0 = m - I_{ph} - b U_0$ and use it to estimate $n_i$ and $|v_i|$. This approximation introduces a systematic underestimation of both ion density and ion drift speed by less than 10%. The following equations are used to derive $n_i$ and $|v_i|$:

$$-I_0 b = \left( -A n_i q_i \frac{v_i^2}{16} \right)^2 = \left( A n_i q_i \frac{v_i}{2m_i} \right)^2 \propto n_i^2 \tag{7}$$

$$-I_0 / b = \frac{m v_i^4}{2q_i} \propto v_i^2. \tag{8}$$

The surface area of the Langmuir probe $A_{LP} = 4 \pi r_{LP}^2$, where $r_{LP} = 0.025$ m is the radius of the probe, and the charge $q_i$ can be used straightforward in Eqs. (7) and (8). The ion mass $m_i$ requires a more detailed investigation since the current $I_i$ is due to different ion species with different masses. Using a simple average mass model is not possible since the density ratio between the different ion species, dominantly hydrogen ions H$^+$ and water group ions W$^+$ (O$^+$, OH$^+$, H$_2$O$^+$, and H$_3$O$^+$) (Young et al., 2005; Sittler et al., 2008), varies both with latitude and radial distance from the planet. A model is derived using CAPS data presented by Thomsen et al. (2010), the method is described in detail in Appendix C.

3. Observations

We use the LP measurements and our model for the ion mass $m_i$ inserted into Eq. (7), to derive the ion densities $n_i$ of the inner magnetosphere. Fig. 3 shows the derived ion densities $n_i$ for orbits 3–133, corresponding to the 1st of February 2005 to the 27th of June 2010. Orbits 80 and 81, covering the dates between the 8th and 22nd of August 2008, are excluded from the analysis, due to a currently unresolved data problem involving these two orbits. Garnier et al. (2012) showed that impacts by suprathermal electrons ($\sim 250–450$ eV) can reach the probe despite a negative bias voltage ($<-5$ V) and give a substantial secondary electron current contribution to the probe. The fitting of the data will in this case give a negative slope $b$. The impacts by the suprathermal electrons resulted in a prominent high current belt located between L shell 6 and 12, which is removed from the plot by excluding all sweeps with $b < 0$. The peak of the secondary electron distribution is located in between 7 and 10 RS (Garnier et al., 2012). Since our method for deriving the photoelectron current uses data from beyond 9 RS and when the estimated electron density was below 0.05 cm$^{-3}$, see Appendix B, the secondary electrons could be suspected to give an error in the measurements. To investigate this possible effect we derived the photoelectron current using only data from outside of 15 RS and received a change in the estimated current of $-0.5\%$. This implies that the original conditions were strong enough. As seen in Fig. 3 the dominant part of the plasma torus is located in between 2.5 and 8 RS, with a north-southward extension of $\pm 2$ RS. The data are divided into a day (right) and a night (left) side, and shows no clear day/night side asymmetry.

Fig. 4 panel a shows the ion densities near the equatorial plane, $|z| < 0.5$ RS. The highest densities are observed at the orbit of Enceladus, at 3.95 RS, which is the data recorded at plume passages during close Enceladus encounters. The sharp peak at $\sim 4.5$ RS belongs to a single ring crossing (orbit 66). The general density structure shows a slower decrease outwards from Saturn, and a faster decrease towards the planet.

Fig. 4 panels b and c shows the radial distance and the density region divided into small bins (0.1 RS and 2.5 cm$^{-3}$), giving the density contribution from each bin. Panel b gives the number of data points for each bin, while panel c gives the probability of the specific bin normalized for each 0.1 RS bin. The black line of panel b shows the power-law fit, $n_{eq} = 2.2 \times 10^{4} (1/R_i^{1.63}$, given by Persoon et al. (2005) using electron densities $n_i$ derived from $f_{ph}$ data from five equatorial orbits. The power-law is derived for the radial distance 5–9 RS and shows a very good agreement with our data in this region. Panel b and c reveal a general density increase leading up to a density maximum closer to the orbit of Tethys. The measured densities at the orbit of Tethys, $\sim 5$ RS, range from $\sim 20$ cm$^{-3}$ to $\sim 110$ cm$^{-3}$, which we believe is a consequence of the dynamics of the plasma disk, this is further discussed in Section 4. No deviations from the general trend can be detected at the orbits of

Fig. 3. The derived ion densities $n_i$ for orbits 3–133, i.e. from the 1st of February 2005 to the 27th of June 2010, plotted in the Saturn Solar Equatorial coordinate system of the planet. The z-axis gives the distance to the planet in north–south direction in RS, and the horizontal axis gives the distance to the axis of rotation in RS. The plot is divided into a day (right) and a night (left) side.
Mimas, Dione, and Rhea. When confining the used area even further, $|z| < 0.5 R_s$, the data shows the same features.

Fig. 5 shows the structure of the plasma torus in north–south direction. Fig. 5 panel a shows the density data measured near the orbit of Enceladus, $4 \pm 0.5 R_s$. For negative $z$-values, i.e. south direction, the high density values corresponding to direct passages through the Enceladus plume are clearly visible. The inner, $|z| \approx 0.75 R_s$, high peak corresponds to the water torus along the Enceladus orbit. The adjacent “wing” structures, detected at $|z| > 0.75 R_s$, correspond to hydrogen ions (Sittler et al., 2008; Thomsen et al., 2010) expanded away from the equatorial plane by a strong ambipolar force (Persoon et al., 2005). The vertical lines labeled M, E, T, D and R show the orbits of the moons Mimas, Enceladus, Tethys, Dione, and Rhea. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

The derived equatorial ion densities $n_i$ at $|z| < 0.5 R_s$ in cm$^{-3}$ as a function of radial distance from Saturn in $R_s$ for orbits 3–133, i.e. from the 1st of February 2005 to the 27th of June 2010, excluding orbits 80 and 81. Panel a shows the location of individual data points and has a $y$-axis limit of 250 cm$^{-3}$ to more clearly show the high density peak at the orbit of Enceladus, which actually peaks at $10^6$ cm$^{-3}$. Panels b and c show the radial distance and the density region divided into small bins (0.1 $R_s$ and 2.5 cm$^{-3}$), giving the density contribution from each bin. Panel b shows the power-law fit $n_{i0} = 2.2 \times 10^6 (1/R_s)^{1.83}$ derived by Persoon et al. (2005) (black line) and the fits $n_i = 1.38 \times 10^6 (1/L_i)^{3.8}$ (magenta line) and $n_i = 627 \exp(-0.517\eta)$ (red line) derived by Thomsen et al. (2010). The vertical lines labeled M, E, T, D and R show the orbits of the moons Mimas, Enceladus, Tethys, Dione, and Rhea. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

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The derived ion velocity $v_i$ is the magnitude of the relative velocity of the ions and the spacecraft. In order to estimate the actual ion velocity we need further assumptions regarding the direction of the ion drift. Earlier investigations of the ion velocities in the E-ring have shown that the ion flows, within 20 $R_s$ are dominantly in the corotational direction, i.e. $v_{i,\theta} \approx v_{i,z}, v_{i,z}$ in cylindrical coordinates (Sittler et al., 2006; Thomsen et al., 2010). Our measured relative velocity $v_i$ is then given by

$$v_i = \sqrt{v_{i,z}^2 + v_{i,\theta}^2 + (v_{i,z} - v_{i,\theta})^2} \quad (9)$$

where $v_{i,z}, v_{i,\theta}$ and $v_{i,\theta}$ is the spacecraft velocity in cylindrical coordinates. Eq. (9) gives

$$v_{i,\theta} = v_{i,z} \pm \sqrt{v_{i,z}^2 - v_{i,z}^2 - v_{i,z}^2} \quad (10)$$

which shows that the actual velocity of the ions, under the assumption $v_{i,\theta} \approx v_{i,z}$, $v_{i,z}$, can be estimated if we know when the spacecraft moves faster than the ions and when it moves slower, which determines the sign of Eq. (10). Assuming that the spacecraft moves faster, i.e. using

$$v_{i,\theta} = v_{i,z} - \sqrt{v_{i,z}^2 - v_{i,z}^2 - v_{i,z}^2}$$

gives velocities lower than Keplerian speed, except for very few cases, and is therefore not a realistic option. This shows that $v_{i,z} < v_{i,\theta}$, in general. So we use

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and estimate the possible error, due to the few cases when the spacecraft actually moves faster than the ion drift speed, to be of the order of a few km/s for a small number of data points. The derived ion azimuthal velocity $v_i$, is presented in Fig. 7.

One source of error in the data are partial ring eclipses. The data have been investigated orbit by orbit to find and adjust for all clear eclipses due to the planet and rings. However, some cases of partial ring eclipses, where the probe current decreases due to the variable absorption of EUV photons by ring particles, are too vague to separate from actual ion current decreases and are therefore not corrected for. Uncorrected ring eclipse cases will give a smaller estimated density $n_i$ and a smaller velocity $v_i$. Since this only involves a small number of points, < 5% of all data, the total effect on the presented results is minor. Another error source

is the assumption that ion flows are mainly in the corotational direction. There is a possibility that significant local radial or vertical ion flows exist in the inner plasma torus, but since most investigations show the contrary (e.g., Sittler et al., 2006; Wilson et al., 2008; Thomsen et al., 2010), our best assumption is a dominantly corotational direction for the ion flows.

It is important to point out the good agreement between the ion densities $n_i$ and the electron densities derived from $f_{ih}$ data, see Fig. C1 and the fit of Fig. 4 panel b. The good agreement between $n_i$ and $n_e$ implies a similar reliability of our derived total ion energy (thermal + ram) from which we derive our presented ion drift velocity $v_i$.

4. Discussion

The RPWS LP derived ion density maps the inner plasma torus of Saturn, showing the dominant part of the torus to be located between 2.5 and 8 Rs. A density maximum, of $10^5$ cm$^{-3}$, is recorded at direct plume passages during close Enceladus encounters, confirming this moon to be a source of volatiles for the E-ring. A slightly different structure is revealed when showing the number of data points for each distance and density bin, Fig. 4 panels b and c. The majority of the data points recorded at the orbit of Enceladus have low density values, $\sim 30$ cm$^{-3}$, Fig. 4 panel c. The same structure is shown when confining the data even further, from $|z| < 0.5 \, \text{R}_S$ to $|z| < 0.1 \, \text{R}_S$, indicating that this feature is not a latitudinal effect. The structure could be explained by the location of the spacecraft at the time of measurement. The high density values, all data above 120 cm$^{-3}$, are collected from passages of the Enceladus plume. When removing all the Enceladus flybys, i.e. passing the moon no closer than 2019 km, the majority of the data are below 120 cm$^{-3}$, making the peak closer to Tethys even more prominent. This clearly implies that Enceladus is a prominent
plasma source, but could also indicate a possible, much less prominent, plasma source at the position of Tethys. Tethys as a plasma source was suggested already at the time of the Pioneer 11 mission, by Frank et al. (1980), who reported the presence of an ion density maximum at the orbit of Tethys. More recently, Burch et al. (2007) backtracked outward-flowing plasma in Saturn’s magnetosphere, finding one source to be at the location of Tethys. However, the above discussed articles also presented similar conclusions for the moon Dione, where our study does not infer an ion density maximum. This could possibly be due to that the time interval for our used data set only contains two Dione flybys and that more and closer flybys would be required for detecting a possible plasma outflow from Dione. Regardless of the cause, it is clear that the role of the icy moons Tethys and Dione has to be further investigated, but this aspect is beyond the scope of this paper.

The fitting of the ion density $n_i$ data to the relation $n_i = 1.38 \times 10^6(1/L)^{0.68}$ derived by Thomsen et al. (2010) shows good agreement in the region $7 < R < 12 \, R_S$, but starts to deviate for $R < 7 \, R_S$ (magenta line Fig. 4 panel b). A better correlation is found with the presented exponential fit $n_i = 627 \exp(-0.517L)$ (Thomsen et al., 2010), see red line of Fig. 4 panel b. Thomsen et al. (2010) used roughly 4.5 years of CAPS data for their estimation. A good agreement is also found with the power-law fit $n_{eq} = 2.2 \times 10^6(1/R_s)^{3.63}$, derived by Persoon et al. (2005). This power-law coincide with our average ion density $n_i$, with most of the data points located within $\sim 10 \, cm^{-3}$ of the power-law fit, in the region $5–12 \, R_S$ (black line Fig. 4 panel b). According to Persoon et al. (2005) this power-law fit is consistent with radial transport due to a centrifugally driven plasma outflow. However, when taking into account all the 129 orbits the broadness of the estimated densities $\Delta n_i$ from $\sim 20 \, cm^{-3}$ to $\sim 110 \, cm^{-3}$ at the orbit of Tethys (Fig. 4), have to be explained by another dynamical process. If the plasma disk fluctuates, then the same location will experience several different densities depending on the time of the measurement. Such time-dependent variation was suggested by Gurnett et al. (2007), who compared the equatorial electron density $n_e$ of the region $3 \leq R \leq 5 \, R_S$ to the Saturn Kilometric Radiation (SKR) longitude location of the spacecraft $\lambda_{SKR}$ for orbits 3–4 and 15–25, i.e. from the 1st of February 2005 to the 19th of March 2005 and the 14th of September 2005 to the 12th of July 2006. The investigation showed a density variation $\Delta n_i$ of $\sim 70 \, cm^{-3}$, depending on the azimuthal location of the spacecraft for a given radial distance, which was explained by a rotating two-cell convection mechanism originally suggested by Dessler et al. (1981) for the Jupiter system. Such, or a similar, mechanism could explain our density span $\Delta n_i$ and further investigation on the dynamical processes in the inner plasma torus will be the topic for our next study.

A rough estimate of our required neutral densities can be made using the continuity equation for the ions, assuming quasineutrality $(n_e \approx n_i)$

$$\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \mathbf{v}_{\text{d}i}) = S_i - L_i = f_i n_0 - a n_i^2,$$

where $\mathbf{v}_{\text{d}i}$ is the ion fluid velocity and we have identified the ion source $S_i$ as the photo- and impact ionization of neutrals given by
the ionization rate $f_i$ and the neutral density $n_n$, and the ion loss process $L_i$ as recombination of ions given by the recombination coefficient $\alpha$ and the ion density $n_i$. Investigating the terms of Eq. (12) shows that only the contribution from ionization, $\alpha n_i^2/f_i$, (assuming steady-state and no radial transport) requires a neutral density $n_n = 9000 \text{ cm}^{-3}$ to be consistent with the estimated $n_i = 30 \text{ cm}^{-3}$ at 4 $R_S$. Sittler et al. (2008) showed that recombination dominated transport for ion losses inside of $L = 5.5$. For the estimation we used $\alpha = 2 \times 10^{-14} \text{ cm}^3/\text{s}$ and $f_i = 2 \times 10^{-8} \text{ s}^{-1}$ (Jia et al., 2010). The value for $f_i$ is a rough average estimate taken into account both photoionization and electron impact ionization. The derived neutral density is in the same order of magnitude as earlier estimates (Ip, 2000; Jurac and Richardson, 2005) leading us to the conclusion that photo- and impact ionization are important processes in the plasma production of the specified region.

The inferred ion velocities $v_{i,0}$ shows a clear general trend, described by $v_{i,0} = 1.58R - 8.8R + 39$, in the region 3.1–6.7 $R_S$. The fitting was carried out using the least square method on all data above Keplerian speed that was located within a bin section with more than 10 data points. The derived $v_{i,0}$ are compared to the ion velocities derived by Wilson et al. (2009) using CAPS measurements from six different days during 2005 and 2006 (black line Fig. 7 panel c). The two data sets are in generally good agreement. Even if the CAPS data show slightly larger ion drift speeds, it is within the range of speeds measured by RPWS/LP. Our velocity data implies that the deviation from rigid corotation starts at around 3 $R_S$, a conclusion which was also suggested by Wilson et al. (2009). Further out the average of the ion velocities $v_{i,0}$ deviates from corotation even further, reaching $\sim 68\%$ of corotation speed at around 5 $R_S$. This is in agreement with the flow speeds presented by Thomsen et al. (2010), who estimated the average velocities to vary between $\sim 50\%$ and $70\%$ of full corotation. The plume of Enceladus is clearly visible as a location where our assumption $v_{i,0} > v_{i,2}$, $v_{i,3}$ is not valid, resulting in many data points with velocities around and below Keplerian speed, see Fig. 7 panel a; the result is also consistent with a further slow down around Enceladus (Morooka et al., 2011).

One possible explanation of the cause of the subcorotation speed $v_{i,0}$ of the ions is given by Sakai et al. (submitted for publication), who used the data set presented in this paper to make a three-component MHD model of the ion speeds. Sakai et al. (submitted for publication) present an investigation of the effect on the ion speeds due to ion-dust coulomb collisions, mass loading, and the magnetospheric electric field. The subcorotation is attributed to the charged dust effect on Pedersen currents in the plasma disk coupled to Saturn’s ionosphere.

The assumption of low thermal effects on the measured ion current, stated in Section 2, needs further investigation. At 4 $R_S$ we estimate an average velocity of $\sim 28 \text{ km/s}$. This is consistent with Wilson et al. (2009) who estimated $\sim 30 \text{ km/s}$ and the estimates of Thomsen et al. (2010) of roughly 15–35 km/s. By excluding the thermal component from our calculations we derive an ion velocity with a small overestimation. Using the ion temperature derived by Sittler et al. (2006) of $\sim 30 \text{ eV}$ for the water group ions at 4 $R_S$, and the equation

$$T_i = \frac{m_i v_{i,0}^2}{2}$$

we infer a thermal speed $v_{i,th}$ of $\sim 18 \text{ km/s}$. This would give an actual average ion velocity of $\sim 21 \text{ km/s}$. The 1–8 eV derived by Wahlund et al. (2009), gives a thermal speed of 3–9 km/s, which would result in an average ion velocity of 27–28 km/s, the overestimation would be negligible for these low temperatures. For 6.5 $R_S$, where the thermal speeds are suspected to have a larger impact on the derived ion velocities than at 4 $R_S$, we estimate an average ion velocity of $\sim 46 \text{ km/s}$, while Wilson et al. (2009) gives $\sim 50 \text{ km/s}$ and Thomsen et al. (2010) gives roughly 35–55 km/s. Using the ion temperature $T_i = 40 \text{ eV}$, as estimated by Thomsen et al. (2010), we derive a thermal speed of 21 km/s. This results in an actual average ion velocity of $\sim 41 \text{ km/s}$. Conclusively, excluding the thermal component in the calculations will result in an overestimated ion velocity $v_{i,0}$, however, this overestimation seems to be of a few km/s and to have a minor influence on the final results. Note the spread in the estimated ion velocities, both present in our study, Fig. 7, and in Thomsen et al. (2010). This spread is likely to be due to the dynamics of the plasma torus, just in the same manner as the ion density spread shown in Fig. 4.

5. Conclusions

- We map the dominant part of the inner plasma torus of Saturn to be located in between 2.5 and 8 $R_S$, with a north-southward extension of $\pm 2 R_S$, Fig. 3.
- No clear day/night side asymmetry is visible in the plasma torus ion density.
- A density maximum, of $10^5 \text{ cm}^{-3}$, is recorded during close flybys of Enceladus, which is the signature of the Enceladus plume.
- The general equatorial density structure shows a slower decrease outwards from Saturn, and a faster decrease towards the planet. The average ion density outward decrease is well described by the equation $n_{eq} = 2.2 \times 10^5 (1/R_S)^{0.3}$, Fig. 4 panel b.
- When excluding all data points recorded closer to Enceladus than 2019 km, the majority of the ion density data are below $120 \text{ cm}^{-3}$ and the equatorial ion density peak is then closer to the orbit of Tethys, at around 4.9 $R_S$. No density peaks are recorded at the orbits of Mimas, Dione, and Rhea, Fig. 4.
- The recorded equatorial ion densities shows a wide spread, with $\Delta n$ of up to 120 cm$^{-3}$, for a chosen radial distance.
- The equatorial ion density north-southward extension shows a high density region within $|z| < 0.75 R_S$, probably corresponding to the water torus along the Enceladus orbit, with an adjacent “wing” structure of lower densities, for $|z| > 0.75 R_S$, probably corresponding to hydrogen ions, Fig. 5. The same kind of structure is also seen at the distance 5 ± 0.5 $R_S$. 

![Fig. A1.](image-url)
We confirm the observations of Wilson et al. (2009) and Thomsen et al. (2010) that the azimuthal velocities of the ions are below full corotation for L shells 3–9, Fig. 7. The deviation from rigid corotation starts at around 3 Rs. Our average ion velocities reach down to ~68% of corotation speed at around 5 Rs.

The ion azimuthal velocity shows a clear general trend in the region between 3 and 7 Rs, with the average velocity described by \( v_{\phi} = 1.5R^2 - 8.7R + 39 \), Fig. 7 panel b.

Our presented data are consistent with a plasma torus where photo- and impact ionization are important processes in the plasma production, based on a simple order of magnitude continuity equation estimate. The spread in both density and velocity data indicates considerable dynamics of the plasma disk, which will be the topic of our future studies based on this data set.

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**Appendix A. Attitude correction**

The m-value, given by the fit shown in Fig. 2, is used to represent the \( I_{ph} \)-current for each sweep. Plotting \( -m \) reveals that the LP measurements on the negative voltage side are dependent on the spacecraft attitude (Fig. A1). Fig. A1 upper panel shows \( -m \) for orbit 21, which is chosen due to its ability to clearly illustrate the attitude dependence. One possible explanation, suggested by Jacobsen et al. (2009), to this dependence is a leakage current from the stub to the probe. The probe receives the same amount of sunlight independent of the spacecraft attitude, due to the spherical probe shape, and should therefore not show an attitude dependence. However, the stub does not always receive the same amount of sunlight since the probe may shade the stub, as illustrated in Fig. 1. This will affect the amount of photoelectrons emitted by the stub, which will cause the current to vary. A leakage current from the stub is a plausible explanation to the attitude dependence of the photoelectron current, but no matter what the cause of the attitude dependence is, it needs to be corrected for. In order to correct for this effect we first derive the regions of interest, i.e. where \( m = I_{ph} \). These regions are found in the outer magnetosphere, where \( I_{ph} \ll I_{ph} \), and when the probe is sunlit, meaning that we exclude planet and moon eclipses, and occasions when the probe is shaded by the spacecraft. So we use the following conditions:

1. the electron density \( n_e \) must be smaller than 0.05 electrons/cm\(^3\),
2. the distance to Saturn have to be larger than 9 Rs, and
3. the angle between the boom of the probe and the Sun has to be smaller than 160°. Conditions 1–3 are in order to avoid shading by planet, moons, or spacecraft, and to assure that \( I_{ph} \ll I_{ph} \), which gives \( m = I_{ph} \).

Using conditions 1–3 we derive regions where the attitude dependence is strong, like the region between the 5th and the 19th of February 2006, shown in Fig. A1. The variation in the current due to the change in attitude can then be estimated, using the assumption that the dependence is linear. Independent of the cause of the attitude dependence we corrected the data using an empirical approach based on the derived statistical sample. We derived the relation between the statistical sample \( m_{orig, ph} \), extracted using conditions 1–3, and the angle between the Sun and the probe with \( m_{orig, ph} = c_1X_{SSE} + c_2Y_{SSE} + c_3Z_{SSE} + d \), (A.1)

where \( c_1, c_2, c_3, d \) are some constants, and \( X_{SSE}, Y_{SSE}, Z_{SSE} \) are the \( X_{SSE} \) components of the spacecraft unit vectors \( X_{SSE}, Y_{SSE} \) and \( Z_{SSE} \) in the Saturn Solar Ellipsoid (SSE) reference system. The SSE reference system has origo in the center of Saturn and is defined as

- \( X_{SSE} \) is along the line from the center of Saturn towards the center of the Sun.
- \( Y_{SSE} \) is given by the cross product \( Z_{SSE} \times X_{SSE} \).
- \( Z_{SSE} \) is parallel to the normal of the orbital plane of Saturn, directed northward.

A least square fit was made to derive the constants \( c_1, c_2, c_3 \). The correction of \( m \) is made by

\[
m = m_{orig} - (c_1X_{SSE} + c_2Y_{SSE} + c_3Z_{SSE}).
\]

where \( m_{orig} \) is the uncorrected current. The lower panel of Fig. A1 shows the corrected data \( -m \).

**Appendix B. Deriving the photoelectron current \( I_{ph} \)**

In order to derive the ion density \( n_i \) and velocity \( v_i \) from Eqs. (3) and (4) with good accuracy, we need to remove the effect of the photoelectron current emitted by the probe, \( I_{ph} \). Photoemission is caused by photons with higher energy than the work function \( \phi \) of the material, which for the titanium nitride covering the RPWI Langmuir probe is \( \phi = 5 \text{ eV} \), so only wavelengths below \( \lambda_{ph} = c / \phi \approx 250 \text{ nm} \) are of interest. This is in the EUV range, where the solar spectrum is much more variable than at visible wavelengths. As we have no independent measurement of the solar UV flux on Cassini, we use the F10.7 radio flux measured daily on Earth. This is useful though not perfect proxy for the wavelength integrated EUV flux, which we propagate from Earth to Saturn assuming that its variation is due only to slowly (solar rotation timescale or longer) evolving structures fixed on the solar surface. With this assumption, we can find a proxy for the UV flux at Saturn at any given time \( t \) by calculating the time \( t_1 < t \) when the Earth last time saw exactly the same face of the Sun (assuming rigid 27 day solar rotation), and the time \( t_2 > t \) when it next time saw that face again. A weighted average of the F10.7 values for these times, \( (F10.7(t_1) \times (t_2 - t) + F10.7(t_2) \times (t_1 - t)) / (t_2 - t_1) \), gives an EUV flux proxy for Saturn after compensating for the decay of the EUV flux with the square of the heliocentric distance. While the method takes reasonable account of slow evolution of features on the Sun, it will fail in cases where e.g., solar flares give short-lived (few days or shorter) increases in the EUV flux. Such transient events will not be adequately treated, but the 27 day period, which is almost always very clear in F10.7 and other solar EUV data, is well compensated for, and the scatter of the data decreases significantly.

The estimated EUV index values are then used to fit a linear relation between the measured photoelectron current and the EUV index. Using this relation makes it possible for us to estimate the measured \( I_{ph} \) at any time when the probe is sunlit.

**Appendix C. Ion mass model**

The plasmasphere in the inner magnetosphere of Saturn is dominated by hydrogen ions \( \text{H}^+ \) and water group ions \( \text{W}^+ \) (\( \text{O}^+, \text{OH}^+, \text{H}_2\text{O}^+, \text{and H}_3\text{O}^+ \)) (Young et al., 2005; Sittler et al., 2008).
This means that our measured current is due to the sum of the current produced by the hydrogen ions and the current produced by water group ions. Neglecting the thermal component, Eq. (1) gives

\[ I_i = -A_{i\mu} n_i q_i \left( \frac{v_i^2}{16} \right) \left( 1 - \frac{q_i (U_1 + U_{bias})}{m_i v_i^2} \right) \]

\[ = \left( -A_{i\mu} n_{iH^+} q_{iH^+} \left( \frac{v_{iH^+}^2}{16} \right) \left( 1 - \frac{q_{iH^+} (U_1 + U_{bias})}{m_{iH^+} v_{iH^+}^2} \right) \right) \]

\[ + \left( -A_{i\mu} n_{iW^-} q_{iW^-} \left( \frac{v_{iW^-}^2}{16} \right) \left( 1 - \frac{q_{iW^-} (U_1 + U_{bias})}{m_{iW^-} v_{iW^-}^2} \right) \right), \quad \text{(C.1)} \]

where \( n_{iH^+}, n_{iW^-}, q_{iH^+}, v_{iH^+}, q_{iW^-}, v_{iW^-} \) are the density/charge/velocity of the hydrogen ions and water group ions, respectively. Using \( q_{iH^+} = q_{iW^-}, v_{iH^+} = v_{iW^-}, \) and \( n_i = n_{iH^+} + n_{iW^-} \). Eq. (C.1) boils down to

\[ \frac{n_i}{m_i} = \frac{n_{iH^+}}{m_{iH^+}} + \frac{n_{iW^-}}{m_{iW^-}}. \quad \text{(C.2)} \]

Inserting the mass of the water group ions, \( m_{W^-} = 18 \text{amu} \) (Sittler et al., 2008), we obtain

\[ m_i \approx \frac{18 n_{iH^+} m_{iH^+} + n_{iW^-} m_{iW^-}}{18 n_{iH^+} + n_{iW^-}}. \quad \text{(C.3)} \]

which shows that the average ion mass \( m_i \) is more affected by the presence of hydrogen ions than water group ions. Using \( m_{iH^+} = 1 \) amu and rearranging Eq. (C.3) we arrive at

\[ m_i \approx \frac{1 + n_{iW^-}}{n_{iH^+}}. \quad \text{(C.4)} \]

The density ratio in the equatorial plane from 6 to 12RS is well described by

\[ \frac{n_{eq,W^-}}{n_{eq,H^+}} = \exp(3.5 - 0.2R), \quad \text{(C.5)} \]

where \( R \) is the distance from Saturn in Rs. Eq. (C.5) is derived from the data presented by Thomsen et al. (2010). Inserting Eq. (C.5) into Eq. (C.4) and using the result in Eq. (7) gives an estimate of the ion density in the equatorial plane of the region \( 6 < R < 12 \text{ Rs} \). To check the validity of Eq. (C.5) a handful of orbits was chosen and compared to electron densities \( n_e \) derived from upper hybrid frequency, \( f_{ub} \), data. For a thorough explanation on how to derive electron densities \( n_e \) from \( f_{ub} \) see Persoon et al. (2005). The two data sets correspond well in the specific region; however, within 6 Rs a much higher density ratio is required for agreement with \( f_{ub} \) data. The best fit is achieved for the assumption of the region closest to Enceladus to be totally dominated by water group ions, giving \( m_i \approx 18 \text{amu} \). To fulfill this requirement and to have a somewhat smooth transition to Eq. (C.5), we use \( n_{eq,W^-}/n_{eq,H^+} = \exp(15 - 2R) \) in the equatorial plane for the region \( R < 6 \text{ Rs} \). The variation of the ion density is not only dependent on the radial distance to the planet, but also on the distance in north–south direction. We follow the expression derived by Persoon et al. (2006) to infer the density ratio variation due to latitude.

\[ \frac{n_{eq,W^-}}{n_{eq,H^+}} = \left( \frac{n_{eq,W^-}}{n_{eq,H^+}} \right) \frac{\exp \left( \frac{L^2}{3H_{eq,W^-}^2} \right)}{\exp \left( \frac{L^2}{3H_{eq,H^+}^2} \right)} \quad \text{(C.6)} \]

where \( L \) is the dipole L shell value, \( H_i \) is the scale height of the ion species \( i \) and \( j \) is the latitude. The scale heights \( H_{eq,W^-} \) and \( H_{eq,H^+} \) for various L shells, in the region \( 6.5 < L < 16.5 \), are estimated by Thomsen et al. (2010). The scale height decreases with decreasing L value and extrapolating the relation given for \( 6.5 < L < 16.5 \) to the region \( L < 6.5 \) gives a good agreement with the available \( f_{ub} \) data, Fig. C1.

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Day/night side asymmetry of ion densities and velocities in Saturn’s inner magnetosphere

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We present Radio and Plasma Wave Science (RPWS) Langmuir probe (LP) measurements from 129 Cassini orbits, which shows a day/night asymmetry in both ion density and ion velocity in the radial region 4-6 Rs (1 Rs=60,268 km) from the center of Saturn. The ion densities ni varies from an average of ~35 cm−3 around noon up to ~70 cm−3 around midnight. The ion velocities vi,θ varies from ~28-32 km/s at the lowest latitudes to ~36-40 km/s at the highest latitudes. The day/night asymmetry is suggested to be due to the radiation pressure force acting on negatively charged mm-sized dust of the E-ring. This force will introduce an extra grain and ion drift component equivalent to the force of an additional electric field of 0.1-2 mV/m for a 10-50 nm sized grain. The additional drift component can explain the day/night asymmetry of the observed ion velocity and ion density.

1. Introduction

The Cassini spacecraft has been orbiting Saturn since July 2004, and are still providing us with a constantly growing amount of data available for statistical analyses. This paper presents a statistical study of the local time (LT) asymmetry of the inner plasma disk of Saturn.

The inner magnetosphere of Saturn is dominated by effects caused by the moon Enceladus. Cassini observations have shown that Enceladus is feeding the E-ring around Saturn with new material through the ejection of water vapor and ice from ridges and troughs located in Enceladus south polar region [e.g., Dougherty et al., 2006]. This creates a neutral torus around Saturn along the orbit of Enceladus. Plasma from the Enceladus plume and charge exchange, photoionization and impact ionization of the neutral torus, creates a plasma torus around Saturn. The plasma in the magnetosphere of Saturn is mostly “frozen” into the magnetic field and therefore tends to be picked-up an corotate with this field (and the planet) by the action of an induced corotation electric field (Erot = -νrot × B). The inner plasma torus of Saturn has been the subject of several studies; Persson et al. [2005] presented electron densities and showed that the measurements were consistent with a centrifugally driven outward plasma flow. Wilson et al. [2009] showed that the plasma subcorotates (~75 % of rigid corotation) beyond 3 Rs, Thomsen et al. [2010] presented ion plasma parameters, e.g. density, composition, and temperatures, derived from measurements by the Cassini Plasma Spectrometer (CAPS) instrument, and Holmberg et al. [2012] used RPWS Langmuir probe (LP) measurements to show that the dominant part of the plasma torus, above ~10 cm−3, is located in between 2.5 and 8 Rs in radial distance and ±2 Rs above/below the equatorial plane. Holmberg et al. [2012] also presented plasma ion densities of the torus, which shows a wide range from just a few cm−3 up to around 150 cm−3 close to the plasma source Enceladus and decreases further away from Enceladus. This is consistent with the plasma electron densities given by Persson et al. [2013].

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to the probe was given by Fahleson [1967] as

\[ I_i \approx I_{i0} \left( 1 - \frac{q(U_i + U_{bias})}{m_i v_i^2} + k_B T_i \right) \]  

\[ (1) \]

where

\[ I_{i0} \approx -A_L P n_i q_i \sqrt{\frac{v_i^2}{16} + \frac{k_B T_i}{2\pi m_i}} \]

\[ (2) \]

is the random current, \( A_{L \rho} \) is the surface area of the Langmuir probe, \( n_i/q_i/v_i/T_i/m_i \) are the density/charge/drift velocity/temperature/mass of the \( i^{th} \) ion species, \( k_B \) is the Boltzmann constant, \( U_i \) is the spacecraft potential measured at the probe (also referred to as the floating potential), and \( U_{bias} \) is the bias voltage of the probe. Relating our intercept value and gradient, derived from the linear fit to the sweeps, to the terms of Equation 1 makes it possible for us to derive the ion number density \( n_i \) and the relative ion velocity \( v_i \). Assuming that the ion flows are dominantly in the corotational direction, \( v_{i,\theta} > v_{i,z} \), \( v_{i,r} \) [Sittler et al., 2006; Thomsen et al., 2010], we can derive the azimuthal ion velocity \( v_{i,\theta} \). A full description of the method used to derive the ion densities \( n_i \) and ion velocities \( v_{i,\theta} \) is given by Holmberg et al. [2012].

3. Observations

The derived ion number density \( n_i \) and ion drift speed \( v_{i,\theta} \) are used to investigate a local time dependence. We use the data recorded for orbit 3 to 133, which corresponds to the 1st February 2005 to the 27th of June 2010, i.e. also including time intervals past equinox. The presented data are limited to 0.5 \( R_S \) in \( z \)-direction, in order to avoid latitudinal variability effects. The data are presented in Figure 1 and 2 as a function of local time where 12 o’clock is defined as towards the Sun and the system is in anti-clockwise direction seen from above Saturn’s north pole. Close encounters with Enceladus have been excluded to avoid effects of the Enceladus plume. This is done by excluding data recorded for closer to Enceladus than 7 \( R_E \) (1 \( R_E = 252 \) km) in the \( x \), \( y \) and positive \( z \) direction and 40 \( R_E \) in the negative \( z \) direction, using an Enceladus centered coordinate system with \( z \) pointing north.

Figure 1a shows the measured ion density in the region 4-6 \( R_S \), this is the region where the asymmetry is most prominent, and also the region with the best data coverage. The data recorded in the LT range 9-15 hrs, the day side, shows lower densities than the data recorded in the night side range. It is important to point out that many orbits have similar orbital parameters and are therefore plotted on top of each other. In this sense, the averages of the recorded data might be a better way to present the measurement results. The averages over all ion density data within each small 0.8 hours and 0.4 \( R_S \) bin are shown in Figure 1b. The ion density in the region from 4-5.5 \( R_S \) varies by an average of around 35 \( cm^{-3} \) at noon up to 70 \( cm^{-3} \) at midnight. Further outwards and inwards from this region the variation is not as prominent. It is difficult to say if the day/night asymmetry is still present in the region 6-8 \( R_S \) due to the lack of data in the region 3-7 hrs. Also the data coverage in the region 6-8 \( R_S \) and the region 6-8 \( R_S \) around noon, which is usually around 30-300 points/bin. Another asymmetry can also be seen in the region 2-4 \( R_S \), which appears to show higher densities in the region 15-23 hrs. This region, 2-4 \( R_S \) and 15-23 hrs, contains few orbits and the data coverage for each bin is around 0-10 points/bin while the coverage in the rest of the region 2-4 \( R_S \) is usually 50-300 data points/bin. Further measurements are therefore needed to investigate a possible asymmetry in this region. Figure 1c and 1d shows the average of larger radial regions, 1d shows the averages of all the data from 2-4 \( R_S \) for each 0.8 hrs bin, and 1c shows the data from 4-6 \( R_S \), the x-axis gives local time and the y-axis gives ion density \( n_i \) in \( cm^{-3} \).

The local time asymmetry is also seen in the derived ion velocity \( v_{i,\theta} \) (Figure 2). Figure 2a shows the measured ion velocity \( v_{i,\theta} \) in the region 4 to 6 \( R_S \), the y-axis gives the radial distance from Saturn in \( R_S \). Figure 1b shows the average of the measured ion density \( n_i \) for each 0.8 hrs bin and 0.4 \( R_S \) bin, for the radial region 2-9 \( R_S \). The figure shows higher density values on the night side and lower values on the day side in the region 4 to 6 \( R_S \). Figure 1c and 1d shows the average of the ion density in the regions 4-6 and 2-4 \( R_S \) for each 0.8 hrs bin.

![Figure 1](image)

**Figure 1.** Day/night asymmetry of the ion density. Figure 1a shows the measured ion density \( n_i \) vs. local time LT in the radial region from 4 to 6 \( R_S \). The y-axis shows radial distance from Saturn in \( R_S \). Figure 1b shows the averages of the measured ion density \( n_i \) for each 0.8 hrs and 0.4 \( R_S \) bin, for the radial region 2-9 \( R_S \). The figure shows higher density values on the night side and lower values on the day side in the region 4 to 6 \( R_S \). Figure 1c and 1d shows the average of the ion density in the regions 4-6 and 2-4 \( R_S \) for each 0.8 hrs bin.

As was presented in Holmberg et al. [2012] the derived ion velocities are slightly overestimated due to the assumption of low ion temperatures. This overestimation is calculated
4. Discussion and conclusions

The local time variation that is seen in the LP measured ion density $n_i$ and, to a smaller degree, also in the ion velocity $v_{i,\theta}$ could be explained by an additional electric field as suggested by Andriopoulos et al. [2012]. Andriopoulos et al. [2012] investigated the drift of energetic electron micro-signatures and could show that the drift was outwards on the dayside and inwards on the nightside. One explanation to the drift would be a noon to midnight electric field of 0.1-1 mV/m strength. Such an electric field would give an additional ion drift velocity, $v = \frac{E_{\text{LP}}}{B_{\text{Sun}}}$, of ~0.6-6 km/s at 5 Rs, directed from dusk to dawn. This corresponds to a velocity difference $\Delta v_{i,\theta}$ of 1.2 to 12 km/s between noon and midnight velocities. The velocity difference derived from the LP measurement is around 5-12 km/s. Wilson et al. [2013] estimated an electric field of 0.38 mV/m at 6 Rs. This would correspond to $\Delta v_{i,\theta} \sim$7.8 km/s, which is in good agreement with the LP results.

A possible cause of the dawn to dusk ion drift (the noon to midnight electric field) over the inner plasma disk is the radiation pressure force acting on the negatively charged dust of the E-ring, the situation is depicted in Figure 3. Recent measurements show that large amounts of negatively charged nm-sized grains are ejected from the plumes of Enceladus [Jones et al., 2009; Hill et al., 2012]. This could give high densities of nm-sized grains in the E-ring outside of the Enceladus plume. The dense inner plasma disk surrounding the E-ring can interact with the charged dust grains near the equatorial plane through electromagnetic forces as a collective dusty plasma ensemble [Wahlund et al., 2009; Morooka et al., 2011]. The dynamics for a dusty plasma are significantly different from the case when considering ions and electrons as the only plasma components [e.g., Goertz, 1989]. In the plasma disk near the equator, $r_d \ll d_g \ll \lambda_D$, where $r_d$ is the grain radius, $d_g$ is the inter-grain distance, and $\lambda_D$ is the Debye length. The charged grains participate in the screening process and in the collective behavior of the plasma. So any force acting on the grains will also be reflected in the dynamics of the ions and electrons. One force that is acting on the dust is the radiation pressure force $F_{\text{rad}} = (I_{\text{rad}}/c)\pi r_d^2$, where $I_{\text{rad}} = L_{\text{Sun}}/4\pi r_d^2 \approx 14$ W/m$^2$ at the distance of Saturn. This would be equivalent to the force from an electric field $E_{\text{rad}} = F_{\text{rad}}/q \approx 0.1$ mV/m (for $r_d = 10$ nm and assuming one charge per grain) and $\approx 9.3$ mV/m (for $r_d = 100$ nm and one charge per grain), acting on the plasma, which is consistent within an order of magnitude with the observationally required electric field values. The simplified model described above does not include collisions, even though collisions should be important in the plasma disk [Sakai et al., 2013]. This needs to be included in a future more detailed investigation of the presented model. Also the complete dust size and charge distribution needs to be taken into account, as well as investigation of the dust-plasma collective coupling effect.

The presented physical explanation to the observations has several merits, e.g.:

- It predicts a minimum in ion drift speed and density close to noon.
- It predicts a day-night asymmetry in several other physical quantities, such as the ones presented in Andriopoulos et al. [2012] and Thomsen et al. [2012].
- It predicts that the effect decreases with increasing radial distance from Saturn, as the dust densities decreases and the dust becomes positively charged beyond ~8 Rs.
- It predicts a preferred radial outflow direction in the equatorial plasma disk.

![Figure 2. Day/night asymmetry of the ion velocity. Figure 2a shows the measured ion velocity $v_{i,\theta}$ vs. local time LT in the radial region from 4 to 6 Rs. The y-axis gives the radial distance from Saturn in Rs. Figure 2b shows the average of the measured ion velocity for each 0.8 hrs and 0.4 Rs bin. The figures shows slightly lower velocities on the day side than on the night side in the region from 4 to 6 Rs. Figure 2c and 2d shows the average of the ion velocity for each 0.8 hrs and 2 Rs bin in the regions 4-6 Rs and 2-4 Rs.](image-url)
A strong coupling between sub-micron charged dust grains and the rest of the plasma components also provides a large inertial component for the plasma disk (angular momentum and rotational energy) since the charged dust contains a dominant part of the mass in the plasma. We therefore find it important to outline this possible explanation for the here presented observations. The suggested model needs to be addressed further, preferably as a hybrid simulation with the dust as a plasma component, but this is beyond the scope of this letter.

Figure 3. Illustration of the presented model. The radiation pressure acting on the nm-sized dust of the E-ring introduce an additional E×B drift component directed from dusk towards dawn. The difference in the azimuthal ion velocity between noon and midnight is detected by the LP as a ∆ν_{ż,θ} ~ 5-12 km/s.

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References


