Pre-biotic molecules and dynamics in the ionosphere of Titan: a space weather station perspective

Licentiate thesis

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Abstract

Saturn’s largest moon Titan (2575 km radius) is the second largest in the Solar system. Titan is the only known moon with a fully developed nitrogen-rich atmosphere with ionosphere extending to ~2000 km altitude, hosting complex organic chemistry. One of the main scientific interests of Titan’s atmosphere and ionosphere is the striking similarity to current theories of those of Earth ~3.5 billion years ago. The Cassini spacecraft has been in orbit around Saturn since 2004 and carries a wide range of instruments for investigating Titan’s ionosphere, among them the Langmuir probe, a “space weather station”, manufactured and operated by the Swedish Institute of Space Physics, Uppsala.

This thesis reviews the first half of the PhD project on the production of pre-biotic molecules in the atmosphere of Titan and early Earth, focusing on the ion densities and dynamics in Titan’s ionosphere derived from the in-situ measurements by the Cassini Langmuir probe.

One of the main results is the detection of significant, up to ~2300 cm³, charge densities of heavy (up to ~13000 amu) negative ions in Titan’s ionosphere below 1400 km altitude. On the nightside of the ionosphere at altitudes below 1200 km, the heavy negative ion charge densities are comparable to the positive ion densities and are in fact the main negative charge carrier, making this region of the ionosphere exhibit properties of dusty plasma. The overall trend is the exponential increasing of the negative ion charge densities towards lower altitudes.

Another important result is the detection of ion drifts that between 880-1100 km altitudes in Titan’s ionosphere translate to neutral winds of 0.5-5.5 km/s. Ion drifts define three regions by altitude, the top layer (above ~1600 km altitude) where the ions are frozen into the background magnetic field, the dynamo region (1100 – 1600 km altitudes) where the ions are drifting in partly opposing directions due to ion-neutral collisions in the presence of the magnetic and electric fields and the bottom layer (below 1100 km altitude) of the ionosphere, where the ions are coupled to neutrals by collisions.
If you try and take a cat apart to see how it works, the first thing you have on your hands is a non-working cat.

— Douglas Adams
List of Papers
This thesis is based on the following papers, which are referred to in the text by their Roman numerals.


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### Abbreviations

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<tr>
<td>CAPS</td>
<td>Cassini Plasma Spectrometer</td>
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<tr>
<td>DC</td>
<td>Direct current</td>
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<td>ELS</td>
<td>Electron Spectrometer</td>
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<tr>
<td>ENA</td>
<td>Energetic Neutral Atom</td>
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<tr>
<td>EUV</td>
<td>Extreme Ultra-Violet</td>
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<td>IBS</td>
<td>Ion Beam Spectrometer</td>
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<td>INMS</td>
<td>Ion and Neutral Mass Spectrometer</td>
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<td>JPL</td>
<td>Jet Propulsion Laboratory (NASA)</td>
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<td>LP</td>
<td>Langmuir Probe</td>
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<td>MSSL</td>
<td>Mullard Space Science Laboratory</td>
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<td>OML</td>
<td>Orbital Motion Limited</td>
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<td>PAH</td>
<td>Polycyclic Aromatic Hydrocarbon</td>
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<td>RPWS</td>
<td>Radio and Plasma Wave Science</td>
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<tr>
<td>s/c</td>
<td>Spacecraft</td>
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<tr>
<td>SKR</td>
<td>Saturn Kilometric Radiation</td>
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<td>SLT</td>
<td>Saturn Local Time</td>
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<td>SZA</td>
<td>Solar Zenith Angle</td>
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<td>SWRI</td>
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Introduction

Saturn and its moons are a miniature model of a solar system. Interaction of its magnetospheric plasma with its moons resembles that of solar wind and planets, its rings offer insights into protoplanetary disks and two of its moons, Titan and Enceladus, may push our definitions of habitability.

Titan is the second biggest moon in our solar system and the only one with a fully formed dense atmosphere (pressure ~1.6 × Earth's at the surface) that extends to more than half its radius above the surface, consisting to 97% of nitrogen and up to 2.7% of methane (Niemann et al., 2005; Waite et al., 2005; Coustenis et al., 2007). The atmosphere is primarily ionized by the solar EUV/X-rays, with lesser contributions from Saturn’s magnetospheric particles and cosmic radiation (Cravens et al., 2005; Wahlund et al., 2005; Ågren et al., 2007; Galand et al., 2010; Shebanits et al., 2013). The ionization triggers complex organic chemistry, forming heavier organics (hydrocarbons), which are thought to be precursors to aerosols (tholins1) responsible for the orange haze of the moon (Sagan et al., 1993; Coates et al., 2007; Waite et al., 2007; Vuitton et al., 2009; Lavvas et al., 2013). The atmospheric composition along with chemistry has been compared to the models of Earth ~3.5 Myrs ago (Pavlov et al., 2003; Tian et al., 2008).

All this leads us to the overarching scientific interest, beginning with the two papers included in this thesis: production of pre-biotic molecules in the atmosphere of Titan and early Earth. We approach the topic from the space physics point of view, focusing on plasma densities and drifts derived from the in-situ measurements by the Cassini spacecraft (s/c).

The Cassini s/c has been in orbit around Saturn since 2004 and has completed 107 targeted flybys of Titan until the end of 2014. A total of 127 are planned until the end of the mission in 2017. The in-situ measurements used in the papers I & II are primarily from the Radio and Plasma Wave Science Langmuir Probe (RPWS/LP), complemented by data from the Cassini Plasma Spectrometer package, Electron Spectrometer (CAPS/ELS) and Ion Beam Spectrometer (CAPS/IBS) as well as the Ion and Neutral Mass Spectrometer (INMS) and the magnetometer (MAG).

Section 1 gives an overview of Titan’s ionosphere and highlights the relevant processes. The basic principles of the instruments are covered in Section 2. Publications are summarized in Section 3. All figures are used with permission from respective publishers.
1 Titan

1.1 Magnetospheric environment

As mentioned above, Titan’s atmosphere is partly ionized by the impacts of Kronian\(^2\) magnetospheric energetic particles, perhaps one of the smallest influences of the giant planet’s magnetospheric environment. The ionosphere is highly conductive and interacts with Saturn’s magnetic field and the magnetospheric plasma it carries, inducing a magnetosphere around Titan complete with an elongated tail and causing exospheric escape of neutrals by charge exchange collisions (Johnson et al., 2010; Strobel et al., 2014, and references therein) and ion escape (Edberg et al., 2011). This interaction resembles that between the solar wind and the ionospheres of Mars and Venus (Nagy et al., 2004). There are two differences though: the direction of incoming magnetospheric plasma is not the same as the Sun-ward direction for Titan, and the Kronian magnetospheric plasma is sub-magnetosonic - no bow shock is formed at Titan (Wahlund et al., 2014). This interaction (shown in Figure 1) influences chemistry in Titan’s ionosphere by energy inputs (energetic particles, collisional heating, plasma waves), introduction of traces of watergroup ions, ion pickup outflows and bulk plasma wake outflows (see e.g. Coustenis et al., 2007; Sittler et al., 2009; Sittler et al., 2010; Wahlund et al., 2014) and may be driving neutral winds in Titan’s thermosphere (Paper II).

The magnetospheric plasma flow at Titan varies periodically (~10.7 h) with Saturn Kilometric Radiation (SKR), the dynamic pressure of the solar wind which causes “flapping” of the plasma sheet (see e.g. Arridge et al. (2008); Morooka et al. (2009) and the references therein) and the seasons of Saturn due to changing inclination of the plasma sheet. Additionally, since Titan’s orbit is at ~20 Saturn Radii (R\(_S\)), the moon may be subjected to the shocked solar wind plasma in Saturn’s magnetosheath (or even solar wind itself) – based on a magnetosphere model, the probability to “catch” Titan outside Saturn’s magnetosphere between Saturn and the Sun has been calculated to 5.5\% (Arridge et al., 2006; Achilleos et al., 2008). Such excursion events have indeed been observed during three Titan flybys to date, T32, T85 and T96 (e.g. Bertucci et al., 2008; Garnier et al., 2009; Edberg et al., 2013b;)

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\(^2\) Saturnian, from Κρόνος, the Greek name of Saturn
Bertucci et al., 2014 (submitted)) – out of 101, consistent with the theoretical estimate mentioned above. For all other flybys Titan has been inside the magnetosphere, bracing the impact of ~120 km/s corotational plasma flow of Saturn’s magnetodisk (Thomsen et al., 2010; Arridge et al., 2012). The magnetospheric plasma also carries with it Saturn’s magnetic field of ~5 nT at Titan’s orbit, directed mainly vertically southwards (Bertucci et al., 2009). The influence of the magnetic field and magnetospheric flux on the ionospheric currents (including neutral winds) is further discussed in the summary of Paper II (Section 3.2).

Figure 1. Schematic representation of the Saturn’s magnetospheric particle and energy input, draping of the magnetic field due to Titan’s induced magnetosphere and energetic neutral atom (ENA) emissions from charge transfer collisions between magnetospheric ions and ionospheric neutrals. Red, yellow and blue waves represent energy inputs from solar IR, visible and UV radiation, resp. From (Sittler et al., 2010), in turn adapted from (Waite et al., 2004).
1.2 Ionosphere: a temporal perspective

*If I have seen further it is by standing on the shoulders of Giants.*  
— Isaac Newton

1.2.1 Previously on Titan…

The investigation of Titan’s ionosphere began with its detection during the first targeted flyby of the moon by Voyager I in 1980, coming as close as 4403 km altitude (Bird, 1997). Two decades before the arrival of Cassini there was only a very limited knowledge of the composition of the atmosphere and ionosphere (Coustenis et al., 2010; Cravens et al., 2010b and references therein). Laboratory experiments suggested the tholins in Titan’s signature orange haze to form from the chemically “close relatives” of methane and nitrogen like polycyclic aromatic hydrocarbons (PAHs) – relatively simple molecules – in the atmosphere around altitudes of few hundred kilometres, where the haze layers were observed by the Voyager (Sagan et al., 1993; Thompson et al., 1994). A big surprise came after arrival of Cassini: the discovery of negative ions by the in-situ CAPS/ELS measurements (Coates et al., 2007). Due to the extreme mass/charge ratios of the negative ions (up to 13800 amu/q) they were gradually accepted as more suitable candidates for aerosol/tholin precursors. Thus the observations of positive and negative ions (Wahlund et al., 2005; Waite et al., 2007; Crary et al., 2009; Sittler et al., 2009; Wahlund et al., 2009b; Coates et al., 2010) and the models based on measurements have led to the current idea: the ionization of the atmosphere initiate the reactions in the top layers of the ionosphere (~1600-1800 km altitude), the ions gradually grow and precipitate, forming aerosols already around ~1000 km altitude, in the lower ionosphere as illustrated in Figure 2. The negative ion masses and densities showed a dependence on altitudes and local time at Titan (Coates et al., 2009; Shebanits et al., 2013; Wellbrock et al., 2013), with stronger presence of higher mass groups towards lower altitudes, which further strengthened the concept.

![Figure 2. Aerosol/tholin formation in Titan’s ionosphere. Adapted from Waite et al. (2007)](image-url)
The formation region of the aerosols and/or their precursors turned out to be situated in Titan’s ionosphere, neatly within reach of the *in-situ* measurements by particle/plasma instruments of Cassini, which can derive a wide set of plasma properties. The measurements relevant for this thesis include: the charge densities of electrons and ions and electron temperatures from the RPWS/LP, neutral densities and masses from the INMS, positive and negative ion mass profiles from the CAPS/ELS and CAPS/IBS. As Cassini accumulated flybys of Titan and with it the data, the shape of its ionosphere was mapped, reflecting the “fluffiness” of the atmosphere of the moon (Figure 3). The ionosphere of Titan extends to about 1800 km altitude (0.7 Titan radii). The RPWS/LP-derived electron density peaks at altitudes around 1050 km dayside and 1150 km nightside (Ågren et al., 2009). Positive ion density peaks at ~1000 km while negative ion density peaks have been observed only occasionally at ~1000 km on dayside and are expected to be below the closest approach altitudes (Shebanits et al., 2013). Negative ion charge density profile from T40 flyby was found to be remarkably similar to aerosol density profile (at ~50 km lower altitude) from an aerosol growth model by Lavvas et al. (2013) for the same flyby, further supporting the scenario of aerosols forming from a mixture of complex organic ions.
Interpretation of the RPWS/LP data (particularly the ion part of the current-voltage sweep characteristics) has come a long way in the last decade. The analysis tools and methods are constantly polished as the software is updated, even though the basic principles do not change. The most “game-changing” events for the analysis of Titan’s ionosphere data were the RPWS/LP measurements of the negative ions and dust (Ågren et al., 2012; Shebanits et al., 2013) and the ion drifts (Paper II). After the discovery of the negative ions by the CAPS/ELS (Coates et al., 2007), their influence was seen in the RPWS/LP measurements already during the first targeted flyby of Titan (Wahlund et al., 2005). However, only after accumulating the RPWS/LP data from a number of flybys could their substantial presence be revealed, more or less forcing their inclusion in the models, measurements and discussions of Titan’s ionosphere (Shebanits et al., 2013). The same extensive dataset was also needed to pinpoint the ion drift effects. These recent findings are summarized in the next section.

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3 http://saturn.jpl.nasa.gov/photos/index.cfm
1.2.2 Recent RPWS/LP results

![Image of Figure 4](image_url)

Figure 4. Altitude vs SZA map of charge densities (colour-coded) in Titan's ionosphere: (a) electrons, (b) positive ions, (c) negative ions. Note the separate colour scale for the negative ions. Adapted from Paper I (Shebanits et al., 2013). Includes flybys TA-T84.

The solar EUV is the main ionization source and as expected, the plasma densities in the ionosphere vary significantly with solar illumination (day-side/nightside and solar cycle) and altitude (Ågren et al., 2009; Edberg et al., 2013a; Edberg et al., 2013b; Shebanits et al., 2013). Typical plasma densities can be inferred from Figure 4, which shows the general structure of the ionosphere:

- on the dayside (SZA < 70°), the ionosphere is clearly dominated by electrons and positive ions; negative ions are present already at ~1200 km altitudes
- over the terminator region (70°<SZA<110°) the overall charge densities gradually decrease while the peaks of the positive ion and electron densities move upwards in altitudes (see also Figure 3)
- on the nightside (SZA>110°) the electron densities drop to ~500 cm⁻³, the ionosphere is dominated by positive and negative ions, exhibiting properties of dusty plasma at altitudes below 1100 km (Shebanits et al., 2013)

With measurements of the mean masses of ions (CAPS/ELS, CAPS/IBS), the magnetic field strength (MAG) and estimation of electric field upper limit of ~3 µV/m (Ågren et al., 2011), the ionosphere can be divided into another three regions by altitude (Figure 5, Paper II):
1. ions are frozen into the magnetic field (negligible collisions, $\vec{E} \times \vec{B}$-drifting magnetospheric ions, yellow-shaded);
2. dynamo region with positive and negative ions drifting in partly opposite directions due to collisions with neutrals in the presence of electric and magnetic fields (red-shaded);
3. collision-dominated region where ions and neutrals move together (blue-shaded in the zoom-in).

![Maximum Ion Velocities for $E = 3 \mu V/m$](image)

**Figure 5.** Color-coded: Maximum ion speed dependence on altitude and neutral winds for $E = 3 \mu V/m$. Dots and circles represent negative and positive ion velocities, resp. Simulated neutral winds of 0-250 m/s demonstrate the coupling of ions and neutrals in the collision-dominated region. Adapted from Paper II.

The ion drifts are relevant for this thesis because they influence the ion transport and (by the continuity equation) the chemistry in Titan’s ionosphere. If the ion drifts in Cassini’s reference frame are directed headwinds (or tailwinds), the ion fluxes measured by the RPWS/LP would increase (or decrease), which translates directly to an increase (or decrease) in the measured ion densities. Since the magnetic and electric fields are required, the ion drifts (and in the deep ionosphere, neutral winds) may be driven by the Kronian magnetospheric plasma flow. The strong collisional coupling between the ions and neutrals below 1100 km altitude has also been shown by Cravens et al. (2010a).

The ion drifts have been previously calculated from a global circulation model (Müller-Wodarg et al., 2008) and derived from a combined analysis of the line-of-sight INMS and CAPS/IBS data from 14 flybys of Titan (Crary et al., 2009) to a modest value of at most 240 m/s at altitudes of 1000-1200 km. However, the ionospheric ion fluxes continuously measured by RPWS/LP along the s/c trajectory during 55 flybys below 1400 km altitude (Paper II) required ion velocities approximately one magnitude larger, translating into
neutral winds of 0.5-2.5 km/s below altitudes of 1100 km (on average, as high as 5.5 km/s during T70). Ion velocities of similar magnitudes were also needed to explain the RPWS/LP measurements during T70 flyby (Ågren et al., 2012) and the dayside-to-nightside ion transport modelled by Cui et al. (2010) based on INMS, RPWS and MAG data. More detailed summary of Paper II results is given in Section 3.2.

1.2.3 In the not-so-distant future

The mean positive ion mass profiles used in analysis of RPWS/LP data were previously derived from measurements by the INMS, which (currently) is limited to particles of up to 100 amu. The CAPS/IBS has virtually no upper limit, but the CAPS instrument has been turned off since June 4th 20124. Using the available data from both INMS and CAPS/IBS instruments, it is possible to introduce a correction for heavy-ions to the INMS dataset. Thus, data from CAPS/ELS, CAPS/IBS and RPWS/LP measurements may be combined to improve upon the existing ionospheric charge density profiles and to derive the average charge of the negative ions.

Cassini mission is planned to end in 2017 and will have toured Saturn’s system for nearly half of a Kronian (and thus Titan) year (29.5 Earth years), providing a great opportunity to study seasonal changes of Titan’s atmosphere and ionosphere. The beginning of the mission (2004) was during Titan’s northern hemisphere spring, with equinox occurring during 2009. In the last years the northern hemisphere of the moon has had summer, which also coincided with solar maximum. The increased ionization by the solar EUV was seen in the measured electron densities in Titan’s ionosphere (Edberg et al., 2013a).

Effect of solar EUV cycle on the ion densities and a multi-instrument case study are topics of ongoing investigations. The end goal of the project is the investigation of implications for the early Earth thermosphere and ionosphere. With the extreme EUV levels and stronger solar wind of a young Sun, the thermosphere of Earth would be extending to few Earth’s radii (Tian et al., 2008), comparable with the weaker magnetosphere modelled by Tarduno et al. (2010) – similar to the interaction of Titan’s ionosphere and induced magnetosphere with the Kronian magnetospheric plasma flow. With respect to its composition, Titan has very limited supply of water in the atmosphere (Kronian magnetospheric water group particles as mentioned above), compared to early Earth. Both environments seem to have the formation of the aerosols/tholins in the ionosphere (Raulin et al., 2010).

2 Measurements

2.1 Langmuir probe theory

Electrostatic probes have been used for measurements of plasma properties for almost a century, based on the theory of current collectors in gaseous discharges (Mott-Smith and Langmuir, 1926). Two years after, the term “plasma” was introduced for a quasi-neutral ionized gas (Langmuir, 1928). Here we review the probe theory for ion measurements in dense plasmas on the example of Titan’s ionosphere.

Orbital-Motion Limited theory

The Orbital-Motion Limited (OML) theory is based on independent trajectories of a particle speed distribution (Maxwellian for our purposes). The trajectories are defined by conservations of energy and (optionally) angular momentum (Laframboise and Parker, 1973).

Key points of the theory are a) no particle originates from the probe and b) the radius of the probe must be (much) smaller than one Debye length ($\lambda_D$, also called “screening length”) - otherwise there will be sheath effects and one should use the so-called Sheath Limited theory instead. The OML works fine for the ionospheric plasma of Titan where $\lambda_D \sim 3 - 7$ cm.

The original equations by (Mott-Smith and Langmuir, 1926) for an isotropic plasma were upgraded by (Medicus, 1962) for space applications where the probe would be moving in plasma. For a spherical probe, the collected ion current $I$ for a set probe potential $U$ is:

$$I = -qnr^2_p \cdot \sqrt{\frac{\pi k_b T}{2m}} \cdot \left[ e^{-A} \cdot \left( 1 - \frac{v_1}{v_{sc}} \right) + e^{-B} \cdot \left( 1 + \frac{v_1}{v_{sc}} \right) + \sqrt{\frac{2k_b T}{mv_{sc}^2}} \right]$$

$$\left( \frac{mv_{sc}^2}{k_b T} + 1 - \frac{2U}{k_b T} \right) \cdot \sqrt{\pi} \left( \text{erf}(\sqrt{A}) - \text{erf}(\sqrt{B}) \right)$$

where $q$, $n$, $m$ and $T$ are ion charge, density, mass and temperature resp., $k_b$ is the Boltzmann constant and $v_{sc}$ is the spacecraft (s/c) speed relative to the plasma (SI units), $A = \frac{m}{2k_b T} (v_1 + v_{sc})^2$, $B = \frac{m}{2k_b T} (v_1 - v_{sc})^2$, $\text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-y^2} dy$, $v_1$ is the minimum relative speed a particle needs to overcome

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⁵ quasi-neutrality: approximately (sufficiently) equal amounts of positive and negative charge carriers
the potential barrier defines as $v_1 = \sqrt{2qU/m}$ for repelling potentials and $v_1 = 0$ for attracting potentials.

OML theory is not locked to spherical probes as it can be applied to cylindrical and general geometry. Interested readers are referred to Laframboise and Parker (1973) who show that the expression for ideal spheres also holds for some deviations from the perfect shape, such as a spherical probe on a boom. However, the ion current has been observed to be linear within the noise level of 100 pA, proving Equation (1) to be unnecessarily complicated. Instead, an approximation by Fahleson et al. (1974) is employed, giving currents as

$$I = \begin{cases} I_0 (1 - \chi) & \text{for attracting potentials} \\ I_0 e^{-\chi} & \text{for repelling potentials} \end{cases}$$

where

$$I_0 = -qnA_{LP} \sqrt{\frac{v^2}{16} + \frac{k_BT}{2nm}}$$

and

$$\chi = \frac{2q|U_{bias}+U_{float}|}{mv^2+2k_BT}$$

$U_{bias}$ is the probe potential and $U_{float}$ is the s/c floating potential$^6$, determined by s/c charging (see Section 2.2 below).

These equations give an extremely good approximation for ion and electron currents compared to the full Medicus (1962) expressions and are far easier to fit to data. For ions, the thermal energy component $k_BT$ can often be neglected$^7$ (since they are heavy) in a fast flowing plasma (= fast flying s/c). Furthermore, for large negative ions $\chi$ is small due to large mass (and for $|U_{bias}| < 4$ V), thus the exponential can be approximated by $1 - \chi$ (large ions give a nearly constant current) (Shebanits et al., 2013).

**Photoelectron current**

An important effect to consider for Langmuir probe measurements in space is the photoelectron emission. Lab experiments by Grard (1973) have shown that although photoelectron current depends on the material, the energy distribution shape is similar and can be approximated by a double-Maxwellian (dominant peak at $\sim 2$ eV). If the photoelectron sheaths of the probe and s/c are overlapping, a “stray” current may leak through.

On a side note, if the LP is mounted on a stub (e.g. Cassini, see Figure 7) rather than a wire boom (e.g. Cluster), the probe may shadow the stub and the s/c may shadow the probe, causing a dependence of the photoelectron current on the s/c attitude (Jacobsen et al., 2009; Morooka et al., 2009; Holmberg et al., 2012).

For Titan’s ionosphere, the photoelectron current is typically negligible, being $\sim 0.1$ times the ion current at altitudes of 1600-1400 km and vanishing

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$^6$ Defined for a certain surface on a s/c, not to be confused with the s/c potential

$^7$ This introduces errors of $<5.6\%$ for ion currents in Titan’s ionosphere below 1400 km altitudes ($\sim 150$ K ions with s/c-relative velocities $> 3000$ m/s), well below the RPWS/LP ion density measurement error of 10%
Measurements

Spacecraft-Plasma interactions

completely due to solar EUV extinction below ~1400 km altitudes. Nevertheless, it is removed in the analysis as a standard procedure via an application of the solar EUV extinction model.

2.2 Spacecraft-Plasma interactions

An object immersed in plasma will be hit by the charge carriers, some giving it the charge and some taking it away. This means that an object in plasma will accumulate potential (in relation to plasma) until the net charge flux is zero. Naturally, for s/c applications it is called the spacecraft potential ($U_{sc}$). In addition, s/c in sunlight will be “ionized” by solar photons (photoelectron emission) as well as impacting particles (secondary electron emission), which may add to the current balance for the s/c potential. These and other related issues are discussed below.

Spacecraft charging

Awareness of s/c charging began with the first ionosphere measurements with rockets. Understanding of the phenomenon has been developing since the launch of Sputnik in 1957. The charging of an object in plasma usually depends only on the electron energies and densities, since the flux of light electrons is typically much larger than flux of much heavier ions. Furthermore, in a dense plasma ($I_{ion}, I_e \gg I_{ph}$) $U_{sc}$ is only dependant on the electron temperature; in a tenuous plasma ($I_{ion} \ll I_e \sim I_{ph}$) it may be used to derive the charge densities (Garrett and Whittlesey, 2000). In dusty plasmas (described below), the metallic plates of a s/c and/or an instrument are subject to triboelectric charging: a charge transfer from dust particles due to frictional contact or a difference in work functions of the dust and metal surfaces (Barjatya and Swenson, 2006), a yet another mechanism that influences the s/c potential. However, so far no extra charging has been detected in dust-rich environments like Enceladus’ plume (Morooka et al., 2011) and deep ionosphere of Titan (Wahlund et al., 2009b).

Potential of RPWS/LP on Cassini is defined relatively to $U_{sc}$ so the latter can be measured “directly”. For Titan’s ionosphere, the Cassini s/c potential is typically very stable on the order of 0.5-1.5 V (Wahlund et al., 2005; Ågren et al., 2007) and the influence of the photoelectron current shifts it between dayside and nightside only by 0.1-0.2 V. Below 1600 km altitude $U_{sc}$ has no impact on the RPWS/LP measurements because the instrument is mounted on a 1.5 m boom, which is much longer than the local Debye length of up to 8 cm. Generally though, the s/c charging is of great concern for all missions and must be taken into account at design stage – depending on the environment, $U_{sc}$ can reach kilovolts (Eriksson and Wahlund, 2006). Usual practice is to make a surface of the s/c conductive so that it has the same potential, avoiding the potential differences that cause arc discharges and fry the electronics.
Wake effects

A s/c in a plasma topic is not complete without discussing wake effects. A wake forms in a supersonic flow behind the s/c, that is when the kinetic energy of plasma ions $m_i v_i^2 / 2$ exceeds their thermal energy $k_b T_i$ (and the s/c potential $eU_{sc}$). Electrons on other hand are subsonic in an ionosphere, which means that while ions are depleted in a wake, electrons fill it up, giving it a negative potential. If the ion kinetic energy is smaller than the s/c potential, the ions will not reach the s/c at all and an enhanced wake will form (Figure 6).

\[
\frac{m_i v_i^2}{2} > k_b T_i, \frac{m_i v_i^2}{2} > eU_{sc}
\]

- Narrow wake

\[
\frac{m_i v_i^2}{2} < k_b T_i, \frac{m_i v_i^2}{2} < eU_{sc}
\]

- Enhanced wake

Figure 6. Wake formation in supersonic plasma. For Cassini case (a) is a typical wake in Titan’s ionosphere while (b) is only relevant for tenuous magnetospheric plasma.

A usual practice is to adjust the s/c attitude as to avoid the wake with the plasma measurement instruments. Yet, however undesirable the wake artefacts may be, some plasma properties can be derived from wake formation - for instance combined measurements of two LP probes and an electron drift instrument can (with application of a simple model) give estimates of the flow velocity vector (Engwall et al., 2006).

During the RPWS/LP measurements of Titan’s ionosphere, the probe was in the s/c wake during (so far) only three early flybys, T3, T8 and T13. T3 and T8 are outside the altitude range relevant for this work, T13 data has been removed from the dataset.

Dusty plasma

Dusty plasmas have been observed in the noctilucent clouds and D-region of ionosphere on Earth (Havnes et al., 1996), Enceladus plume (Morooka et al., 2011), E-ring of Saturn (Kurth et al., 2006; Srama et al., 2006), deep ionosphere of Titan (Shebanits et al., 2013) and cometary comas. A dusty plasma is defined by the so-called dusty plasma condition, $r_d \ll d \ll \lambda_D$, i.e. the dust grain radius $r_d$ must be small compared to the intergrain distance $d$, which in
turn must be smaller than Debye length $\lambda_D$. When this condition is met, the dust particles exhibit collective behaviour because they are coupled to the plasma, which is then called “dusty plasma”. Otherwise, the system is referred to as “dust in plasma” (Shukla, 2001; Morooka et al., 2011).

Dust particles in a plasma resemble tiny s/c:s: electrons will stick to them and charge them negatively in the same way (Horányi et al., 2004; Wahlund et al., 2009a). Density of electrons in such dusty plasma decreases with increasing dust density. For instance, a study by Morooka et al. (2011) shows that the depletion of electrons in Enceladus plume is nearly 100%. Although not so extreme, electron depletion is also the case in the deep (<1100 km altitude) ionosphere of Titan, reaching electron to positive ion density ratios of ~0.1 (Shebanits et al., 2013). In such cases, the dust particles become primary negative charge carriers.

Dusty plasma exhibits different properties than “normal” plasma because of the much heavier negative particles (compared to positive ions). Heavier ions have more inertia and their motion is less affected by the electromagnetic forces – but because of their charge they still influence the rest of plasma. An example of such different behaviour is Kronian E-ring, populated by the dust from Enceladus (Kurth et al., 2006, and references therein), where the dust velocities are tending towards Keplerian\(^8\) motion rather than not following the corotation of the magnetospheric plasma.

### 2.3 Details of ion measurements

**Langmuir Probe (RPWS/LP)**

Part of the Radio Plasma and Wave Science (RPWS) package of Cassini s/c, the Langmuir Probe has been built and is operated by the Swedish Institute of Space Physics. It is a spherical probe with diameter of 2.5 cm, mounted on a 1.5 m boom and has three modes of operation, voltage sweep, density and cleaning (for more detailed description, see Gurnett et al., 2004; Wahlund et al., 2009a; Morooka et al., 2011)

\(^8\) Here: governed by gravity
Figure 7. RWPS/LP, engineering model. The red arrow marks the stub that has same potential as the probe.

Voltage sweeps measure the current to the probe for voltage ranges of $\pm 32\, \text{V}$ or $\pm 4\, \text{V}$ (for targeted flybys of moons) every 24 s, shifting the voltage in 512 steps under 0.5 s (for Titan flybys the speed of Cassini s/c is about 6 km/s, limiting the spatial resolution of the probe to $\approx 3\, \text{km}$). Targeted flybys usually have double-sweeps (down and up), giving 1024 points. Furthermore, to avoid capacitive charging effects\(^9\), the current is sampled twice, just after the voltage shift and just before the next shift (see Figure 8). Voltage sweep mode is used for simultaneous measuring of electron and ion characteristics.

For the density mode the probe is put at a constant voltage, allowing to sample the current with a high frequency (20 Hz). This mode is typically used for electron measurements. The cleaning mode is regularly used to remove any possible contamination of the probe surface. This is done by setting the probe to large negative potential ($-100\, \text{V}$), thus sputtering the surface with high energy ions.

\(^9\) Capacitors in the circuitry don't allow the current to instantly adapt to the voltage change
Figure 8. Examples of ±4 V (left) and ±32 V (right) voltage sweeps (top) with corresponding currents (bottom). Zoomed in areas show the double-sampling.

To derive ion parameters, analysis of sweep data is performed as follows:

1. The double-sampled current values are averaged and double-sweeps (if any) are folded into one to increase amount of data points.
2. The current is fitted to a linear curve $m = a + U \cdot b + I_{ph}$, yielding the slope $b$ and the DC-current $a$. The photoelectron current $I_{ph}$ can be removed in Titan's ionosphere by applying a simple solar extinction model for the dominant atmospheric species (Ågren et al., 2007).
3. Plasma densities, temperatures and speeds may be derived from the obtained fit parameters. Due to the “simplicity” of the ion current theory the analysis process can be largely automatized.

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As mentioned in Section 2.1, the photoelectron current is negligible in the ionosphere of Titan below 1400 km altitude as discussed in Section 2.1.
Figure 9. Current fit example from Titan flyby T56. Blue crosses show the total sampled current, red dots show the electron current for positive probe bias and the instrument noise for negative bias.

**Ion and Neutral Mass Spectrometer (INMS)**

Built at NASA’s Goddard Space Flight Center’s Planetary Atmospheres Laboratory and the University of Michigan’s Space Physics Research Laboratory, INMS is a high-resolution particle instrument for measuring masses of neutral gas and ions up to 100 amu (Mandt et al., 2012). It has two modes of operation, closed ion source and open ion source (see Figure 10).

In *closed ion source*, the neutral gas collides with the walls of the spherical antechamber, attaining thermal equilibrium. Pressure gradient (created by the antechamber geometry) pushes the gas to the ion source, where it is ionized by electron guns and focused into the quadrupole mass analyser by electrostatic and quadrupole switching lenses.

In *open ion source*, the ions (or ionized neutrals) are again focused into the quadrupole mass analyser by the quadrupole switching lens. When neutrals are measured, ions are filtered out (trapped) by the deflectors in the cylindrical antechamber. When ions are measured, the neutrals are not ionized and do not react to the quadrupole switching lens. The charged particles are then processed by the quadrupole mass analyser that separates them by mass-to-charge ratios.
Electron Spectrometer (CAPS/ELS)

The Electron Spectrometer (ELS) is a part of Cassini Plasma Science package (Figure 11) manufactured by the Mullard Space Science Laboratory (MSSL). The instrument is a hemispherical top-hat electrostatic analyser, thus the angular and energy resolution is limited by its geometry and the micro-channel plate (8 anodes, 20° each). During a measurement, ELS sweeps through log-spaced voltages in accumulation intervals of 31.25 ms (for Titan, the default mode is used: 64 steps covering 0.6-28000 eV). Being an electrostatic analyser, ELS actually detects energy/charge, which is then converted to mass/charge. This must be kept in mind when looking at the negative ion data from ELS as the negative ions may have multiple charges – as the fact that the instrument was built to measure electrons, detection of negative ions was a major discovery for Titan (see e.g. Coates et al., 2007).

Ion Beam Spectrometer (CAPS/IBS)

Similarly to CAPS/ELS, the Ion Beam Spectrometer (IBS) is a curved-electrode electrostatic analyser (Figure 11) made by the Southwest Research Institute (SWRI). It is designed for high-resolution measurements of positive ion flux over 0.6-28250 eV energy range. During operation the instrument performs a voltage scan in 255 steps over 2 s and can potentially cover 80% of all space (Young et al., 2004). Translating energy coverage to mass, IBS may provide mass/charge measurements up to ~1500 amu, thus covering the vast majority of positive ion species in Titan’s ionosphere.
Figure 11. Cassini Plasma Spectrometer layout showing position and schematic representation of the IBS and ELS instruments. Adapted from (Young et al., 2004).
3 Summary of publications

3.1 Paper I

*Negative ion densities on the ionosphere of Titan – Cassini RPWS/LP results*

**Authors:**


**Journal:**

Planetary and Space Science

**Status:**

Published

**Summary:**

In this paper we investigate the distribution of charge densities of positive and negative ions, as well as electrons, in Titan’s ionosphere. A total of 47 flybys below 1400 km altitude were used, between Oct 2004 and July 2012. The charge densities were mapped to solar zenith angle and altitude, with main result being the significant amount of the negative ions, particularly on the nightside and below altitudes of 1000 km, where the free electrons are much less abundant than the ions \( n_e/n_+ \sim 0.1 - 0.7 \) - effectively increasing the ionization levels (typically based only on the electron densities).

Consistent with previous measurements, the main ionospheric peak is seen at altitudes increasing towards the terminator region. Negative ion charge densities increase exponentially with decreasing altitudes (down to the lowest flown altitudes of 880 km), reaching up to 2500 cm\(^{-3}\). Measured positive ion densities reach values of 4200 cm\(^{-3}\). The depletion of electrons on the nightside, together with large negative ion charge densities, imply dusty plasma properties: the dominant negative charge carriers are the heavy negative ions, with \( 10^4 \text{-} 10^6 \) ions/Debye cube. Negative ions are predicted to have 1-2 charges.
Lower negative ion charge densities around the ecliptic polar regions as compared to the ecliptic equatorial region are another confirmation of the importance of the solar EUV for the ion production. Magnetospheric plasma impacts on the ionization was also investigated but no correlation was found.

**My contribution to Paper I:**

I performed the RPWS/LP ion data analysis and had the main responsibility for writing the paper.

### 3.2 Paper II

*On Ion Drifts and Neutral Winds in Titan’s Thermosphere*

**Authors:**


**Journal:**

Journal of Geophysical Research

**Status:**

To be submitted

**Summary:**

In this paper we investigate apparent deviations from the charge neutrality condition measured by Cassini RPWS/LP in the ionosphere of Titan at altitudes below 1400 km. The dataset used for this study consists of 55 flybys. Total ion current measured by the instrument consists of positive and negative ion fluxes, which if added together must match the independently measured electron flux. As mentioned in Section 1.2.2, the ion drifts affect the ion fluxes measured by the RPWS/LP. In Paper I this effect has been circumvented by using the electron density derived independently from the electron characteristics instead of the total ion density derived from the ion characteristics.

The resulting differential ion flux is defined as the difference between the positive and negative ion fluxes to the probe. Ionospheric origin of the differential ion flux is evident as it is only measured in deeper parts of Titan’s ionosphere, below ~1400 km.

The collisions with neutrals become more important with decreasing altitude. Based on measurements of the positive and negative ion average masses, neutral densities and magnetic field, one of the results of this study is division of the ionosphere into three layers: above 1600 km, the ions are frozen into
magnetic field; between 1100 and 1600 km (dynamo region), collisions with neutrals in the presence of electric and magnetic fields force the ions to drift in opposite directions; below 1000-1100 km, ions are moving with neutrals, the measured differential ion flux at these altitudes therefore translates into the neutral winds with strength averaging to 0.5-1.5 km/s on the dayside and 1.5-2.5 km/s on the nightside (up to 5.5 km/s during T70 flyby), the main result of this study. Most fluctuations of the differential ion current in the dynamo region are measured near the north polar part of Titan’s ionosphere and may be explained by currents closing into Saturn’s corotational magnetospheric plasma flows. There is (yet) no flyby coverage near the south polar part of the ionosphere, where a similar picture is expected.

My contribution to Paper II:

I planned the study, performed the RPWS/LP ion data analysis, contributed to the method development and had the main responsibility for writing the paper.

3.3 Papers not included in this thesis:

I performed the RPWS/LP ion data analysis.
4 Bibliography


