On the Formation and Structure of the Ionosphere of Titan

KARIN ÅGREN
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Abstract

We present results on the ionospheric structure around Titan observed during numerous deep (<1000 km) flybys by the Cassini spacecraft. Our results are based on measurements by the radio and plasma wave science instrument, in particular the Langmuir probe. In addition, data from the magnetometer and electron spectrometer have contributed.

The ionosphere of Titan is created when the atmosphere of the moon becomes ionised. There are several mechanisms that contribute to this, the most important of which are considered to be photoionisation by EUV from the Sun with associated photoelectron ionisation, and particle impact ionisation by electrons and ions from Saturn’s corotating magnetosphere.

We investigate the influence of the solar zenith angle on the electron number density at the ionospheric peak. The results show on average four times more plasma on the dayside compared to the nightside, with typical densities of 2500 – 3500 cm$^{-3}$ and 400 – 1000 cm$^{-3}$, respectively. In a complementary study, we make a case study of a nightside flyby and show that the altitude structure of the deep ionosphere is reproducible by a simple electron impact ionisation model. Taken together, this leads to the conclusion that solar photons are the main ionisation source of the dayside ionosphere. However, magnetospheric particle precipitation also contributes and can explain the electron densities seen on the nightside.

As Titan does not exhibit any large intrinsic magnetic field, the fact that it is embedded in the magnetosphere of Saturn means that the Kronian field drapes around the moon and gives rise to an induced magnetosphere. We show that there are currents of the order of 10 – 100 nA m$^{-2}$ flowing in the ionosphere of the moon. Associated with the currents are perpendicular electric fields ranging from 0.5 to 3 μV m$^{-1}$.

Finally, we investigate measurements obtained during T70, the deepest Titan flyby performed to date. We show that there is a substantial amount of negative ions present below an altitude of 900 km. This confirms previous result by the electron spectrometer, showing negative ions at higher altitudes in Titan’s ionosphere.

Keywords: Titan, Cassini, space physics, ionisation, electron density, ionosphere, negative ions, electric currents, electric fields, solar zenith angle, Langmuir probe

Karin Ägren, Uppsala University, Department of Physics and Astronomy, Box 516, SE-751 20 Uppsala, Sweden.

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Hall äätt ennåm dine nuww
se ta ve i för sju a töuww
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...böxern rämmnes

Tallarn va ju toong å dröuww
se hall äätt ennåm dine nuww
för janna ska eint nanteing
...ogjort lämnes
List of Papers

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

On magnetospheric electron impact ionisation and dynamics in Titan’s ram-side and polar ionosphere - a Cassini case study

On the ionospheric structure of Titan

Detection of currents and associated electric fields in Titan’s ionosphere from Cassini data

IV Ågren, K., Edberg, N. J. T. and Wahlund, J.-E.
Detection of negative ions in the deep ionosphere of Titan during the Cassini flyby T70

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Papers not included in the thesis.

Model-data comparisons for Titan’s nightside ionosphere

II Rosenqvist, L., Wahlund, J.-E., Ågren, K., Modolo, R., Opgenoorth, H. J., Strobel, D., Müller-Wodarg, I., Garnier, P. and Bertucci, C.
Titan ionospheric conductivities from Cassini measurements

Structure of Titan’s ionosphere: Model comparisons with Cassini data

On the amount of heavy molecular ions in Titan’s ionosphere

Titan’s ionosphere in the magnetosheath: Cassini RPWS results during the T32 flyby

Dynamical and magnetic field time constants for Titan’s ionosphere: Empirical estimates and comparisons with Venus

Ion transport in Titan’s upper atmosphere

VIII Edberg, N. J. T., Wahlund, J.-E., Ågren, K., Morooka, M. W., Modolo, R., Bertucci, C. and Dougherty, M. K.

Electron density and temperature measurements in the cold plasma environment of Titan: Implications for atmospheric escape


Structured ionospheric outflow during the Cassini T55-T59 Titan flybys


Recent Results from Titan’s Ionosphere


Comparisons of Cassini flybys of the Titan magnetospheric interaction with an MHD model: Evidence for organized behavior at high altitudes
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1. Introduction

The Age of Exploration was a period in history from the early 15th century to the early 17th century. During these years, an intensive exploration of the continents took place, which helped to create the first comprehensive map of the planet. More than 350 years later, on October 4, 1957, the Soviet Union launched its first satellite, Sputnik, into space. This marked the beginning of a new era: The Space Age. Although it may be argued that this era was initially driven by a competition between the Soviet Union and the USA, the Space Age is still ongoing and characterised by the will to explore and discover entirely new areas, this time, however, all beyond Earth.

This thesis serves as one contribution to the exploration of space and is concentrated on Titan, the largest moon of Saturn. Titan hosts the most chemically and dynamically complex atmosphere in the Solar System, which makes it interesting to study for several reasons. By investigating processes occurring in Titan’s ionosphere we learn more about planetary evolution. Like Mars and Venus, Titan is a suitable subject for comparative studies of the Earth.

Titan orbits inside Saturn’s magnetosphere, which leads to a complex and interesting ionisation situation, with solar photons and incoming magnetospheric electrons both contributing to the ionisation of the atmosphere. The fact that Titan is situated within the Kronian magnetosphere also means that the moon strongly interacts with Saturn’s magnetic field, which drapes around the moon to form an induced magnetosphere.

All results in this thesis are based on measurements made by the Cassini spacecraft, which is orbiting Saturn and regularly passes by Titan. Before the arrival of Cassini in 2004, not much was known about Titan. Measurements have revealed a moon with a much more complex and intricate behaviour than first expected. The results we provide have therefore been received with great curiosity and interest, by ourselves, as well as by others in the scientific community. Together with the other instrument teams we have made a considerable progress in the last few years, although there is still much to be investigated and many new discoveries to be made.

The aim of my research is to closely study the deep ionosphere of Titan and investigate the influence of various ionisation sources on its formation. I have made case studies of two specific flybys: one on the nightside, to study the importance of impacting electron ionisation; and one very deep flyby, where the Langmuir probe for the first time could be used to detect a substantial amount of negative ions. In addition, I have carried out a statistical study of
several flybys in order to investigate the dependence of the ionisation on the solar zenith angle. Furthermore, I have looked at the electrodynamical coupling between Saturn’s magnetosphere and Titan’s ionosphere, which induces currents in the ionosphere of the moon.

This thesis consists of six introductory chapters accompanied by four scientific publications. The introductory part is meant to give a background to my research and put the scientific publications into context. Chapter 2 gives a brief introduction to plasma physics and typical plasma regions around a planetary body. Chapter 3 focuses on Titan, and particularly its ionosphere, with special attention to its creation, structure and chemistry – featuring both negative and positive ions – as well as the dynamics caused by Saturn’s magnetospheric plasma flowing past the moon. In Chapter 4, the instrumentation that has been used to obtain the results of this thesis is presented, and in Chapter 5 we discuss the results and put them into a greater context. In particular, I relate the findings to the orange haze around Titan, and discuss possible haze formation mechanisms. Concluding the first part of the thesis, Chapters 6 and 7 provide English and Swedish summaries of the papers. The second part of the thesis is formed by four peer-reviewed scientific papers.
2. The space environment

In school, we learn that matter can exist in three different states. Water, for example, may be found either as a solid (ice), liquid, or in the gas phase (water vapour). This way of dividing materials into only three states is a simplified way of looking at things, though most of the time sufficient to describe conditions on Earth. However, as soon as we leave Earth’s atmosphere, matter is most commonly found in the fourth state: plasma. Plasma is by far the most common state of visible matter in the universe; in fact, more than 99% of the baryonic matter of the universe is in the plasma state. Plasma differs from solids, liquids and gases in that its atoms are divided into free electrons and free ions.

In this Chapter the concept of plasma, the solar wind, and two main plasma regions of a planetary body – the ionosphere and the magnetosphere – are introduced.

2.1 Plasma properties

By definition, a plasma is: "A quasineutral gas of charged and neutral particles which exhibits collective behaviour" [10]. The term quasineutral implies that \( n_e \approx n_i \), where \( n_e \) is the electron density, and \( n_i \) is the ion density. Collective behaviour is a feature of a plasma meaning that the motion of the particles is governed by long-range electromagnetic forces, rather than collisions. To understand the behaviour of a plasma, we need to consider Maxwell’s equations:

\[
\nabla \cdot \mathbf{E} = \rho / \varepsilon_0 \tag{2.1}
\]

\[
\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} \tag{2.2}
\]

\[
\nabla \times \mathbf{B} = \mu_0 \left( \mathbf{j} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right) \tag{2.3}
\]

\[
\nabla \cdot \mathbf{B} = 0 \tag{2.4}
\]
where $\mathbf{E}$ is the electric field, $\mathbf{B}$ is the magnetic field, $\rho$ is the net charge density, $t$ is time, and $\mu_0$ and $\varepsilon_0$ are the permeability and permittivity of free space, respectively.

Equation 2.1, known as Poisson’s equation, tells us that the total electric flux out of a closed surface is proportional to the charge enclosed by the surface. Equation 2.2, Faraday’s law, describes how a magnetic field that changes in time can act as a source of an electric field. Similarly, Ampère’s law, Equation 2.3, shows how an electric current becomes a source of the magnetic field. Finally, Equation 2.4, known as Gauss’ law, tells us that the magnetic flux out of any closed surface is zero.

When combined with Lorentz’s equation, which describes the force acting on a charged particle moving in an electromagnetic field, and Newton’s second law, which relates the force, acceleration and mass of the particle, these equations are in principle sufficient to model the behaviour of a (non-relativistic) plasma.

*Debye shielding* is an example of the collective behaviour of a plasma. As the plasma consists of positive and negative charges, it will work to shield out electric potentials that are applied to it. A charged object that is immersed in a plasma creates a cloud of charge by attracting or repelling other particles; normally, electrons. The *Debye length*, $\lambda_D$, is a measure of the shielding distance of a sheath and is given by

$$\lambda_D = \sqrt{\frac{\varepsilon_0 k_B T_e}{n q_e^2}}$$

(2.5)

where $k_B$ is the Boltzmann constant, $T_e$ the electron temperature, $n$ the plasma density, and $q_e$ the electron charge. If the dimension of a system, $L$, is much larger than $\lambda_D$, then local concentrations of charge are shielded out in a distance that is short compared to $L$, leaving the bulk of the plasma free of large electric potentials or fields.

Since the plasma can carry currents, it is capable of creating and sustaining a magnetic field. For a highly conducting plasma, this field will be closely connected to the ions and electrons creating it, and will therefore move with the plasma. This direct relation between particles and the magnetic field is referred to as the *frozen-in condition*, as the magnetic field can be looked upon as frozen into the particles or vice versa. This condition prevents plasma from one magnetic region to transfer to a region with different magnetic topology and leads to the formation of plasma regions, separated from each other by thin current sheets. Occasionally, the magnetic fields of two plasma regions in space are allowed to merge, and by doing so mixing two types of plasma. Diffusion and plasma wave activity may also transfer matter, momentum and energy between two plasma populations on adjacent magnetic flux tubes.

Plasma measurements will be discussed in more detail in Chapter 4.
2.2 The ionosphere

The atmosphere of Earth consists of gas layers tied to Earth by gravitation. It is composed mainly of molecular nitrogen (78%) and molecular oxygen (21%). At most, the atmosphere reaches up to altitudes of around 1000 km, but as the atmosphere gradually becomes thinner with altitude, most of the atmospheric gas is found within a few kilometres from the surface. Figure 2.1 shows temperature and density profiles of Earth’s atmosphere that can be divided into four regions. The lowest layer, called the troposphere, contains approximately 80% of the atmosphere’s mass. The average depth of the troposphere is about 17 km.\(^1\) Above it lies the stratosphere, which is stratified in terms of temperature, with warmer layers higher up, and cooler layers lower down (in contrast to the troposphere, where the warmer layers are found closest to the ground). At around 50 km, the stratosphere ends and the mesosphere begins. In the mesosphere, the temperature trend again reverses, i.e., the layers become cooler with altitude. The upper boundary of the mesosphere is the coldest naturally occurring place on Earth, where temperatures can fall below 130 K (-143\(^{\circ}\) C). Situated above the mesosphere, the thermosphere is characterised by the fact that atmospheric gases sort into strata by diffusion according to their respective molecular mass. As seen in Figure 2.1, atomic oxygen is the lightest species, followed by molecular nitrogen and molecular oxygen. Temperatures in the thermosphere are highly dependent on solar activity and differ vastly between solar minimum and solar maximum.

The ionosphere is defined as the upper ionised part of the neutral atmosphere. The source of this ionisation can be either photons, impacting energetic particles, cosmic rays, meteoric impacts, or a combination thereof. A photon or other particle is capable of ionising the atmosphere if its energy (\(h\nu^2\) or kinetic) exceeds the binding energy of the valence electron to the neutral atmospheric species. If this is the case, the electron is released and the end result is an atomic or molecular ion and a free electron.

Depending on, e.g., variation in composition, location in the Solar System and the properties of the neutral atmosphere, every ionosphere is unique and may vary depending on solar conditions, changes of the neutral atmosphere and incoming ionising particles. All ionospheres generally show at least one peak in electron density at some altitude, above which there are not enough neutral particles to ionise, and below which the atmosphere becomes so dense that the ionising particles or photons cannot penetrate further. An ionosphere can also have several electron density peaks at different altitudes, corresponding to different ionisation sources.\(^3\) On the dayside of Earth we find four iono-

---

1. All altitudes given above are approximate, and can vary both seasonally and as a function of latitude.
2. Where \(h\) is Planck’s constant and \(\nu\) is the frequency.
3. Atmospheric chemistry and convection can also play a role in the creation of the peaks.
spheric layers, called the D, E, F₁, and F₂ layer. This is illustrated in Figure 2.2.

Titan’s ionosphere also displays a number of peaks that originate from different ionisation sources. The main peaks that will be discussed in this thesis are created by solar photon ionisation and ionisation by impacting electrons. The ionosphere of Titan will be discussed in greater detail in Chapter 3.

2.3 The magnetosphere

According to a formal definition, a planetary magnetosphere is the region surrounding a planetary body within which its own magnetic field dominates the behaviour of electrically charged particles [5]. This applies to the most common type of magnetosphere, which is found around a planetary body with an internal magnetic field. In our Solar System, e.g., Earth, Saturn, Jupiter, Mercury, and Ganymede belong to this group. However, what might reasonably be called a magnetosphere can also be found around planetary bodies lacking an internal magnetic field. The magnetosphere is then a result of induction; we therefore call it an induced magnetosphere. In this case, the magnetosphere is formed when a time-varying external magnetic field acts upon a planetary body that is either electrically conducting by itself or equipped with a substantial ionosphere, as is the case for Titan [39].
The properties of the magnetosphere can vary a great deal between different bodies, depending on the strength and orientation of the magnetic field, the density and spread of the plasma, and the distance to the Sun. There is a broad variety of magnetospheres in the Solar System, ranging from small-scale magnetospheres around Mercury and Ganymede to an extremely large and complex one around Jupiter. The induced magnetospheres of Mars, Venus and Titan exhibit many similarities. They are all caused by the interaction of an external wind of plasma with their ionospheres. Further similarities include the fact that photoionisation seems to be the most important ionisation process; that a clear outer boundary of the induced magnetosphere can be found; and that the magnetotail geometry of each body follows the orientation of the upstream magnetic field and flow velocity under quasi-steady conditions[6].

The magnetospheres of Earth and Saturn, depicted in Figure 2.3, are created through interaction between the solar wind and the magnetic field of the planets. The solar wind is a stream of high-speed ionised particles, mostly electrons and protons, that are ejected from the upper atmosphere of the Sun. Since the solar wind travels at supersonic speeds, and hence cannot sense the magnetised obstacle soon enough to move smoothly around it, a bow shock forms on the sunward side of the magnetosphere. In the magnetosheath, situated between the bow shock and the magnetopause, solar wind plasma dominates, whereas on the other side of the magnetopause, the plasma is mostly asso-
associated with the magnetised body. Under certain circumstances, the magnetic field travelling with the solar wind plasma merges with that of the planet. As a result, magnetic field lines are dragged to the anti-sunward side of the planet, where they form a stretched out magnetotail. This merging, or reconnection, of the magnetic field lines is a complex and not yet fully understood process.

The magnetosphere of Saturn differs from that of Earth in a few important respects. It is larger relative to the size of the planet, and the plasma within its inner regions is denser; a consequence of the many moons of Saturn, in particular Enceladus, constantly refilling the magnetosphere with plasma. Saturn’s magnetosphere extends roughly 1.5 million kilometers ($\approx 25$ Saturn radii) sunward of the planet and, because of the drag of the solar wind, more than ten times that distance in the opposite direction. A large part of the Kronian magnetosphere essentially corotates with the planet, which is not the case at Earth. The corotation period is approximately 10.7 hours [3], which is much faster than the motion of the moons. This means that the plasma will hit the moons and by so doing strongly interact with them, e.g., by ionising their atmospheres. A more detailed discussion of the interaction between the Kronian magnetosphere and Titan is given in Chapter 3.
Figure 2.3: A comparison between Earth’s magnetosphere (upper) and Saturn’s magnetosphere. Image credit: NASA.
3. Titan

Titan – the largest moon of Saturn – is an interesting object to study for several reasons. To begin with, it hosts a very dense atmosphere, composed mainly of molecular nitrogen and believed to partly resemble the atmosphere of Earth a few billion years ago, before life emerged on our planet. Also, when Titan’s atmosphere becomes ionised, a complex ionosphere with an intricate ion chemistry is created. In fact, Titan hosts the most complex ionosphere in the Solar System. The processes involved – both the creation of the ionosphere and its interaction with the variable external space environment, as well as the resulting ionospheric composition – are the subject of Papers I, II, and IV of this thesis. Furthermore, Titan is embedded in Saturn’s magnetosphere, making it possible to study the electrodynamical coupling between Titan’s ionosphere and Saturn’s magnetosphere. In Paper III, we study the magnetic field at and around Titan and give a first view of how electric currents in the moon’s ionosphere are flowing.

In this Chapter we give a general introduction to Titan’s atmosphere and ionosphere. We focus on the formation and structure of the ionosphere, and also describe in more detail the positive and negative ions that have been detected therein. The Chapter ends with a discussion of how studies of Titan might give interesting clues as to what once occurred on Earth.

3.1 Basics

The radius of Titan is 2575 km, making it the second largest moon in the Solar System, only dwarfed by Jupiter’s moon Ganymede. Although being just a moon, Titan is comparable in size to Mars, and is bigger than both Mercury and the dwarf planet Pluto. Despite its size, it is not possible to see Titan from Earth with the naked eye. However, if you know where to look, a pair of binoculars is sufficient to catch a glimpse of the moon.

In 1979, Pioneer 11 made the first flyby of Titan. One year later, Voyager 1 first detected the ionosphere of the moon by an onboard radio occultation experiment [9]. The breakthrough, however, came when the Cassini spacecraft entered the Saturn system. Since the first flyby of Titan in October 2004, more than 80 successful flybys of the moon have been conducted to date. In Figure 3.1 an image taken by the Cassini spacecraft shows Titan as it would appear to the human eye.
Titan is located within Saturn’s corotating magnetosphere at a distance of 20.3 Saturn radii ($1 \, R_S \approx 60268$ km) from the planet. The field and particle conditions upstream of Titan are important in controlling the interaction between the moon and Saturn [8, 45, 46]. Saturn’s corotating magnetospheric plasma, which also carries the magnetic field of the planet, impinges on Titan. Titan’s electrically conducting ionosphere acts as an obstacle to the flowing plasma, but as the flow is subsonic, no bow shock is formed. Nevertheless, the plasma flowing past Titan drapes the time-varying magnetic field around the moon, forming an induced magnetosphere. As a consequence, an induced magnetotail forms in the tail region of the magnetosphere. As Titan rotates around Saturn in the corotation direction, but slower than the corotating plasma, the tail is leading Titan in its orbit, as shown in Figure 3.2. The direction of the tail depends on the impinging plasma flow from Saturn, which can vary significantly in direction and about two orders of magnitude in density [4, 7, 41]. This coupling between Titan’s and Saturn’s space environments gives rise to currents flowing in the ionosphere of the moon. In Paper III, we describe a multi-instrumental study investigating the magnitude and direction of these currents. For all flybys with favourable conditions we were able to infer currents flowing in the ionosphere of Titan. These currents were of the order of 10 to 100 nA m$^{-2}$. This is, to the best of our knowledge, the first time that currents in Titan’s ionosphere have been observed.
The orbital distance of Titan is just smaller than the average distance of the sub-solar point of Saturn’s magnetosphere. Thus, Titan is most of the time located within the magnetosphere of Saturn, but may also be found in the magnetosheath or even in the solar wind plasma, depending on the current solar wind conditions. During two flybys so far, T32 and T42, Titan has been observed in the magnetosheath; however, no observations have yet been made of Titan in the solar wind. Investigations of the plasma environment around Titan have established that the moon is usually found in one of four different plasma regions [45]. These are: plasma sheet, lobe-like, magnetosheath, and bimodal. Bimodal encounters contain two distinct electron populations with the low energy component apparently associated with water group ions. Out of the 54 flybys included in the study, 34 could clearly be associated with one of the above groups. The rest were classified as a combination of several, or remained unclassified. 19 flybys were classified as occurring in the plasma sheet, eight as lobe-like, five as bimodal, and two in the magnetosheath. There was a trend towards more unclassified flybys in the post noon sector, which

Figure 3.2: Wake orientations at different local times around Saturn’s orbit. Adapted from [11].
Table 3.1: The physical and orbital parameters of Titan

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equatorial radius, $R_T$</td>
<td>2575 km</td>
</tr>
<tr>
<td>Mass</td>
<td>$1.35 \times 10^{23}$ kg</td>
</tr>
<tr>
<td>Density</td>
<td>1.88 kg m$^{-3}$</td>
</tr>
<tr>
<td>Distance from Saturn</td>
<td>20.3 $R_S$</td>
</tr>
<tr>
<td>Escape velocity</td>
<td>2.64 km s$^{-1}$</td>
</tr>
<tr>
<td>Gravity acceleration</td>
<td>1.35 m s$^{-2}$</td>
</tr>
<tr>
<td>Pressure at surface</td>
<td>1.5 bar</td>
</tr>
<tr>
<td>Temperature at surface</td>
<td>94 K (-179°C)</td>
</tr>
<tr>
<td>Orbital period</td>
<td>15.95 days</td>
</tr>
<tr>
<td>Spin period</td>
<td>Synchronous (15.95 days)</td>
</tr>
<tr>
<td>Axial tilt</td>
<td>0°</td>
</tr>
<tr>
<td>Eccentricity of orbit</td>
<td>0.029°</td>
</tr>
</tbody>
</table>

might be explained by a more disturbed dusk flank region of the Kronian magnetosphere.

The global features of Saturn’s magnetospheric field have also been a subject for classification [46]. Three basic upstream environment classes were defined: magnetodisc lobes, lobe with current sheet features, and current sheet-like. 62 flybys were investigated and the most common class was found to be current sheet-type fields both inbound and outbound that were found in 22 cases. Furthermore, quiet lobe-type fields both inbound and outbound were observed on nine occasions. Often, current sheet fields were observed on one side of the encounter with lobe-type on the other. This is in accordance with our observations in Paper III, where out of 17 flybys, we find only three that show similar magnetic conditions before and after the passage of Titan.

Table 3.1 lists some of Titan’s main properties.

3.2 The atmosphere

The most abundant constituent in Titan’s atmosphere is molecular nitrogen, N$_2$, followed by several percent of methane, CH$_4$, and several tenths of percent of molecular hydrogen, H$_2$ [55]. Figure 3.3 shows the main species of Titan’s atmosphere, as measured by the ion and neutral mass spectrometer (INMS) during 20 inbound legs of Titan flybys. N$_2$ is by far the most abundant constituent at low altitudes, whereas CH$_4$ and H$_2$ represent comparatively minor contributions. At altitudes above 1500 km, the atmospheric gases start to sort into strata according to molecular mass, as discussed in Chapter 2. The orange haze surrounding Titan, known as Titan’s organic haze, is an effect of the complex organic chemistry producing heavy aerosols, often referred to as
tholins. The exact formation mechanisms of these tholins are not known, but recent discoveries by the Cassini spacecraft of both heavy positive and negative ions in Titan’s ionosphere are providing important clues to understanding this. The tholin formation will be discussed in further detail in Chapter 5. Now we will take a closer look at the creation of Titan’s ionosphere.

Figure 3.3: The main species in Titan’s atmosphere. N₂ is shown as filled circles, CH₄ as squares, and H₂ as triangles. Adapted from [40].

3.3 The ionosphere
Solar photons and incoming magnetospheric particles, as well as cosmic rays and impacting meteorites, may collide with the neutral atoms and molecules in Titan’s atmosphere and, by removing electrons, convert them into ions; see e.g., [17, 43, 26] and references therein. This leads to the formation of an ionosphere around the moon. Figure 3.4 shows a compilation of measurements and models of Titan’s ionosphere. Above 300 km, the electron density is measured by the Cassini radio science investigation (RSS) onboard Cassini [33], while the ion and electron densities further down are measured by the Huygens lander [38]. The grey areas show the positions of the haze layers at Titan. The main haze layer lies closest to the ground and the detached haze layer is found further up. Three main ionisation layers are visible in the figure; one just above 1200 km, one around 550 km and the lowest one at approximately 50 km. These peaks are thought to originate from precipitating electrons, precipitating ions and cosmic rays, in that order. The correlation between the
positions of the haze layers and the cosmic ray and proton production peaks suggests that the haze is created by the ions resulting from the precipitation of these particles [29].

![Figure 3.4](image)

**Figure 3.4:** Electron density regions in Titan’s ionosphere. Solid and dotted lines represent data from the radio occultation experiment and the Huygens lander. Dashed lines represent model outputs and the positions of the haze layers are shown in grey. Adapted from [29].

### 3.3.1 Structure of the ionosphere

The appearance of Titan’s ionosphere is variable, mainly depending on solar conditions. The main peak is often found in the region around 1000 - 1150 km altitude, and is shown to be caused by solar photons, sometimes with an addition from suprathermal electrons [26].

Deep Cassini flybys of Titan generally reach an altitude of around 950 km above ground. Four plasma regions are typically encountered during a Titan flyby. As long as the spacecraft passes low enough, an ionospheric peak, where the electron density reaches its maximum, is seen. The peak altitudes vary between flybys, but in Paper II we conclude that all investigated flybys showed an electron peak altitude between 1000 and 1400 km. Depending on the configuration of the flyby and the nature of the peak, Cassini sometimes passes well below the peak and at other times just barely touches it at closest approach (CA). Above the main peak, the density slowly decreases. At the exobase, the ionosphere transforms from being chemically controlled to dynamically controlled. The exobase marks the beginning of the exo-ionosphere, which is characterised by an exponentially decreasing electron density. The
extent of the exo-ionosphere is highly variable, and plasma of ionospheric origin has in extreme cases been detected even at seven Titan radii \((1 R_T \approx 2575 \text{ km})\) from the moon. At such large distances from the moon, however, in most cases the plasma originates from Saturn’s magnetosphere. The electron density of the Kronian magnetosphere usually is around \(0.1 \text{ cm}^{-3}\) at Titan’s orbital distance [41].

Figure 3.5 shows altitude profiles of the electron density and temperature taken from 52 Titan flybys [22]. The black lines represent the median values. All regions that were discussed above can be identified in the figure. The electron temperature changes from average values of just below 1 eV in the magnetosphere, to only a few hundreds of eV in the deep ionosphere of Titan. From altitudes close to the ionospheric peak, and below, the temperature stays stable at between 0.03 and 0.06 eV (350 - 700 K), as also seen in Paper II of this thesis. This behaviour of the electron temperature is thought to originate from the fact that it depends on the magnetic field configuration [27].

\[\text{Figure 3.5: Electron density and temperature as a function of altitude. Adapted from [22].}\]

### 3.3.2 Dayside ionosphere

Before Cassini’s arrival at Saturn, it was debated whether solar photons or magnetospheric impacting electrons were the main ionisation source of Titan’s dayside ionosphere. Now, with data from more than 80 Titan flybys available, the picture has become much clearer, although many questions still remain. Figure 3.6 shows the electron density at the peak versus solar zenith angle (SZA), adapted from our Paper II. Superposed is the data from the Cassini
radio science investigation, which derives the electron density from Titan occultations. Hence, they obtain the electron densities near dawn and dusk. The ionisation on the dayside (<100°) is strongly dependent on the SZA. The magnitude of the electron density peak decreases with SZA, while the peak altitude of the ionisation increases with SZA (shown in Paper II). From this we conclude that solar photons are the main ionisation source on the dayside of Titan. A broad transition region between SZA 50° and 100° can be identified in Figure 3.6, where the ionosphere of Titan changes from sunlit to shaded by the moon. The radio occultation measurements are all found in this region and may be divided into two subsets: one with ’normal’ density values that show good agreement with our results, and one with ’disturbed’ density values that are higher than expected. The latter are likely to be the result of intense electron precipitation [32]. Later, Galand et al. [26] studied four dayside flybys in order to distinguish the influence of the solar photon ionisation from other possible ionisation sources. They found that solar radiation is the dominant ionisation source between 1050 km and 1200 km, but in the SZA interval 85° - 110°, the presence of suprathermal electrons of non-solar origin was also seen to contribute. The most probable origin of these electrons is the corotating magnetosphere of Saturn.

Figure 3.6: The electron peak density as a function of SZA in Titan’s ionosphere obtained from the RPWS/LP (reproduced from our Paper II) and the RSS. Adapted from [32].
3.3.3 Nightside ionosphere

Publications on nightside flybys of Titan are scarce. However, studies have shown that ionisation by magnetospheric impacting electrons is sufficient to account for the electron density seen on the nightside. In Paper I, we study the Cassini nightside flyby T5 in detail. By using a simplified ionospheric model, we estimate the electron density during the flyby. As input to the model we use neutral atmosphere measurements from INMS and incoming electron fluxes given by the electron spectrometer (ELS) of the Cassini plasma spectrometer (CAPS) instrument. We conclude that in order to achieve a reasonably good agreement between the modelled and the measured electron densities, we need to divide the incoming flux by a factor of ten; a result that was confirmed by [19]. From this, we draw the conclusion that the bulk of the ions seen on the nightside of Titan are produced through electron impact ionisation. Furthermore, it has been suggested that part of the ions detected on the nightside of the moon may be explained by day-to-night transport, especially in the case of heavy species with long recombination times [20].

3.4 Composition of the ionosphere

Titan’s upper atmosphere and ionosphere feature the most compositionally complex ionospheric chemistry in the Solar System. More than 50 different ions have been inferred at, or above, the mass detection limit of the INMS in the ionosphere of Titan, with distinct groups separated by 12-14 amu/q. An additional several hundreds to thousands of ion species are expected and remain to be identified in the future [18, 51, 52]. In the case of solar radiation and electron impact ionisation, the largest primary production rates occur for the most abundant neutral species, N2 and CH4, leading to the production of N2+, N+ and CH4+. These ions, however, rapidly convert into other ion species. In Paper I, we treat the ionisation of molecular nitrogen and the dominant reactions following from that. Our reaction scheme is based on a model by [31], including the main reactions:

\[
N_2^+ + CH_4 \rightarrow CH_3^+ + N_2 + H \quad (3.1)
\]

\[
CH_3^+ + CH_4 \rightarrow C_2H_5^+ + H_2 \quad (3.2)
\]

\[
C_2H_5^+ + HCN \rightarrow HCNH^+ + C_2H_4 \quad (3.3)
\]

In Equation 3.1, molecular nitrogen ions react with methane to produce CH3+. In the next step, CH3+ ions react with methane to produce C2H5+, which then reacts with HCN to produce the main abundant species; HCNH+. Although
not shown here, we also include the production of a couple of higher mass nitrile species, C₃H₂N⁺ and C₅H₅N⁺. Lastly, we infer an electron density by summing the ion densities. A more detailed description of the chemical reactions included in our model is found in [1].

3.4.1 Positive ions

Figure 3.7 shows the ion and neutral mass spectra obtained between 950 km and 1000 km, during T19. Due to the instrument design, the INMS has an upper detection limit of 100 amu. As can be seen in the figure, the ions are still numerous at 99 amu, giving a first indication that ions heavier than so are present in the ionosphere. The ion beam spectrometer (IBS) can also measure ions, though not with the same mass resolution as INMS. The IBS has a one count level of approximately 300 amu [14].

Wahlund et al. [53] provided a first multi-instrument study of the ion abundances in Titan’s deep ionosphere. Ion and electron measurements from INMS, IBS, ELS and the Langmuir probe (LP) were combined in order to estimate how much of the matter in Titan’s deep ionosphere consists of ions heavier than 99 amu. During three specific flybys, T17, T18 and T32, heavy positive ions approached 50 - 70% of the total ionospheric density below the ionospheric peaks. There was also a trend of higher densities of heavy molecular positive ions towards lower altitudes. This result was confirmed by a subsequent study comparing INMS and IBS ion densities, which showed that ions at energies corresponding to 100 - 200 amu appear below approximately 1200 km and often represent the dominant ion species below 1000 km [15].

3.4.2 Negative ions

An unexpected feature of Titan’s ionosphere was the presence of heavy negative ions. The electron spectrometer onboard Cassini was put on the spacecraft in order to measure electrons. What they did not foresee was that the instrument would also be able to detect negative ions. When the spectrometer is pointing in the ram direction, heavy negative ions can enter the instrument and show up in the data as peaks in the spectrogram. During all flybys reaching altitudes below 1400 km, with the instrument pointing in a favourable direction, negative ions have been detected [12, 13]. Figure 3.8 displays the negative ions detected during the Cassini flyby T40. A statistical study showed that the maximum negative ion mass is higher at low altitudes and at high latitudes. Furthermore, a weak dependence of the maximum mass on SZA was found, with a tendency to find highest masses near the terminator [13]. Before the arrival of Cassini, negative ions were not assumed to be important for the chemistry in Titan’s ionosphere – at least not at these high alti-
tudes. Hence, the discovery of negative ions meant that the chemical models for Titan had to be revised, see e.g., [50].

In Paper IV, we detect negative ions during flyby T70 by use of the LP. T70 is the deepest flyby of Titan to date, with a CA of 880 km. We conclude that negative ions are present with a density ranging from about 1000 to over 10 000 cm$^{-3}$/Z, and a velocity (relative to ground) from a few hundred m s$^{-1}$ up to a few km s$^{-1}$. This implies that the negative ion population is either much more numerous than expected, or moving at a higher velocity than previously thought possible.

3.5 Implications for Earth

Although Titan is much colder than Earth,$^1$ the two still exhibit many similarities. For instance, the atmospheres of both bodies have the same main constituent: N$_2$. Furthermore, they share a similar structure from the troposphere to the thermosphere and the surface pressures are comparable (1 bar at Earth, compared to 1.5 bar at Titan). The temperatures at Titan do not allow water to be liquid at the surface. On the other hand, in the temperature range of the moon, methane can exist as a gas, liquid and solid. Methane therefore seems to play the role of water on the Earth, being cycled between the atmosphere and the surface. Even more interestingly, analogies can be made between the current organic chemistry on Titan and the prebiotic chemistry of the primitive Earth. In this respect, the aerosols of Titan are of particular interest. Laboratory experiments have shown that once in contact with liquid water, Titan tholins can release many compounds of biological interest, including amino acids. Titan might therefore be used as a laboratory to study some of the processes that may have been involved in the prebiotic chemistry at Earth; processes that cannot be studied here, as long-term chemical evolution is impossible to study in an Earth-based laboratory. The fact that Titan’s atmosphere consists of molecular nitrogen and methane makes it one of the most favourable ones for prebiotic synthesis [35].

$^1$Titan has a surface temperature of 94 K (-179$^\circ$C).
Figure 3.7: INMS ion and neutral spectra between 950 and 1000 km during T19. Note the regular mass peak spacing of 12-14 amu, as expected for compounds consisting of carbon and nitrogen. Adapted from [56].
Figure 3.8: Energy-time spectrogram centred on the T40 encounter. The colour scale on the right is proportional to the electron differential energy flux. Negative ions are seen as sharp vertical spikes between 21:27 and 21:34 UT. Adapted from [13].
Cassini-Huygens is an international collaboration between NASA, ESA, the Italian Space Agency and numerous instrument suppliers from institutions in Europe and the USA. The mission consists of an orbiter, Cassini, and a landing probe for Titan, Huygens. The launch took place at Cape Canaveral in October 1997 and slightly less than seven years later, in July 2004, the spacecraft reached Saturn. The nominal mission of Cassini ended already in 2008, but as the spacecraft had worked nearly flawlessly, the mission was extended, first to the end of 2010, and then all the way to 2017. Plans are that the mission will end in a grandiose finale, when Cassini will crash into Saturn while making the first measurements of the deep ionosphere of the planet.

The science objectives for Cassini include investigations of Saturn, its magnetosphere and rings, as well as closer studies of several of the numerous (> 60) moons of the planet, with special focus on Titan. For Titan, the main objectives have been to determine the most abundant elements present and the relative abundance between them, to increase the knowledge about the formation and evolution of Titan’s atmosphere and ionosphere, to study global winds and temperatures, and to investigate Titan’s surface properties. The main focus of this thesis is on the structure and formation of the ionosphere, where we have provided the first comprehensive view of Titan’s ionospheric structure at different SZAs, investigated the contribution of electron impact ionisation, and contributed to the characterisation of the negative ion observations.

In this Chapter we will introduce the instruments from which data are used in the work presented in this thesis.

4.1 Instrumentation

Cassini, depicted in Figure 4.1, is equipped with a total of twelve science instrument suites. Each suite, consisting of several sensors, is designed to carry out various scientific studies of Saturn and its moons. The results in this thesis are based on data from four of the instrument consortia: the radio and plasma wave science (RPWS), the cassini plasma spectrometer (CAPS), the magnetometer (MAG), and the ion and neutral mass spectrometer (INMS).
4.1.1 Radio and plasma wave science

The RPWS measures plasma waves, radio signals from Saturn, dust and meteorid distributions in the Kronian system, as well as numerous plasma parameters – the latter essential for the work conducted in this thesis. The RPWS consists of three electric field sensors; three search-coil magnetic field sensors; high, medium and wideband receivers; and a Langmuir probe (LP). This thesis is primarily based on the LP data, but the electric field data are at times used to confirm the measurements. Thus, we have two independent ways of measuring the electron density. For a more comprehensive description of the RPWS instrument package, see [30].

The Langmuir probe

The LP was put on the spacecraft in order to measure the cold plasma properties around Saturn, as well as in the close vicinity of Titan during targeted flybys through the moon’s ionosphere. Figure 4.2 shows the LP onboard Cassini, which is a spherical 5 cm diameter sensor mounted on a boom 1.5 m from the spacecraft main body. The LP can be operated in two modes: sweep and continuous. In the sweep mode, the bias voltage of the probe is swept
from -4 to +4 V in 512 steps during most Titan flybys.\(^1\) One sweep occurs every 24 s, and during this time, the LP continuously samples the total electric current from the plasma. The analysis of the resulting current-voltage curves determines several plasma parameters, such as the electron and ion densities, \(n_e\) and \(n_i\), the electron temperature, \(T_e\), the ion velocity, \(v_i\), and the mean ion mass, \(m_i\). The LP measurements also provide the spacecraft potential, \(U_{SC}\).

Figure 4.2: The Langmuir probe onboard the Cassini spacecraft. Image credit: IRF.

Depending on the ratio between the LP radius and the Debye sheath, there are two limiting cases to consider; orbital motion limited (OML) and sheath limited (SL). In OML theory the size of the LP is assumed to be very small compared to the plasma sheath. This implies a weak screening effect, and that the motion of a single charge can be considered to be independent of the motion of other charges and to be mainly governed by the probe potential. If, on the other hand, the probe has a radius equal to, or larger than, the Debye sheath, the screening effect becomes important and the properties of the Debye sheath will change with the charge accumulation. Our analysis is adapted to SL theory according to \([57]\); however, since the Debye sheath is generally rather thick inside Saturn’s magnetosphere, we achieve in principle the same results as for OML theory. Within Titan’s dense and cold ionosphere, sheath effects are indeed detectable at times. If OML theory is used in these cases, no significant variation in output results is obtained. Therefore, and since OML theory is simpler to explain, we discuss only OML theory below.

Normally, the total current sampled by the LP consists of three components: the ion, the electron, and the photoelectron currents, respectively. The ion current here is assumed to be made up of positive ions. At times, an ion current due to negative ions also needs to be included.

\(^1\)If the flyby has a CA above 1200 km: \(± 32\) V in 1024 steps.
The general expression for the current sampled by a Langmuir probe\(^2\) is given by the electron and ion currents, \(I_e\) and \(I_i\), here jointly denoted as \(I_x\), and given by either

\[
I_x = I_{x0}(1 - \chi_x) \tag{4.1}
\]

or

\[
I_x = I_{x0}\exp(-\chi_x), \tag{4.2}
\]

depending on the bias voltage of the probe. For a negative bias voltage, the ions are sampled according to 4.1 and the electrons according to 4.2, whereas the opposite applies for a positively charged probe. \(I_{x0}\) is given by

\[
I_{x0} = -A_{LP}n_xq_x \sqrt{\frac{v_x^2}{16} + \frac{k_B T_x}{2\pi m_x}}, \tag{4.3}
\]

where \(A_{LP}\) is the surface area of the probe, \(n_x\) is the electron or ion density, \(q_x\) is the electron or ion charge, \(v_x\) is the electron or ion velocity, \(k_B\) is the Boltzmann constant, \(T_x\) is the electron or ion temperature, and \(m_x\) is the electron or ion mass. The first term in the radical is the flow kinetic energy term, and the second is the thermal energy term. \(\chi_x\) is given by

\[
\chi_x = \frac{q_x(U_{\text{bias}} + U_{\text{probe}})}{m_xv_x^2 + k_B T_x}, \tag{4.4}
\]

where \(U_{\text{bias}}\) is the bias potential and \(U_{\text{float}}\) the spacecraft potential measured at the probe.

When the LP is positively charged, the electron current dominates the measurements, whereas a negatively charged probe primarily measures the ion current. Consequently, the main measured currents are:

- For a positive bias voltage, the main current sampled is made up by electrons. In this case the flow kinetic energy term can be neglected as it is much smaller than the thermal energy term. This gives us:

\[
I_e = I_{e0}(1 - \chi_e), \tag{4.5}
\]

where \(I_{e0}\) is the random electron current given by

\[
I_{e0} = -A_{LP}n_ee \sqrt{\frac{k_B T_e}{2\pi m_e}}, \tag{4.6}
\]

\(^2\)According to OML theory.
and $\chi_e$ is given by

$$\chi_e = \frac{q_e (U_{\text{bias}} + U_{\text{float}})}{k_B T_e}. \quad (4.7)$$

If $U_{\text{float}}$ is known, the spacecraft potential may be estimated from

$$(U_{\text{SC}} - U_{\text{float}}) = c U_{\text{SC}} \cdot e^{-d_{LP}/\lambda_D}, \quad (4.8)$$

where $d_{LP}$ is the distance to the probe from the spacecraft main body, $\lambda_D$ is the Debye length of the surrounding plasma and $c \approx 5/6$ is a constant [53].

- For a negative bias voltage, the sampled current is assumed to be dominated by the ion ram flux to the probe. This means that the thermal energy component, $k_B T_i$, is assumed to be negligible, which gives us the following expression for the current:

$$I_i = I_{i0} (1 - \chi_i), \quad (4.9)$$

where $I_{i0}$ is the ion current given by

$$I_{i0} = -A_{\text{LP}} n_i q_i \frac{|v_i|}{4}, \quad (4.10)$$

and $\chi_i$ is given by

$$\chi_i = \frac{q_i (U_{\text{bias}} + U_{\text{probe}})}{(m_i v_i^2)/2}. \quad (4.11)$$

Negative ions will look like a current of very heavy electrons in the analysis. This means that the equations valid for electrons will apply, but with the difference that the thermal energy component can be disregarded, given that the kinetic energy component is much larger.

In the continuous mode, the electron current is sampled with 20 samples per second at a constant bias voltage of $+4 \, \text{V}$. Sampling in the continuous mode between the sweeps yields better time resolution of the data. According to Equations 4.5 - 4.7, the measured current is proportional to

$$\sqrt{T_e n_e \left(1 + \frac{1}{T_e} (U_{\text{bias}} + U_{\text{SC}})\right)} \quad (4.12)$$

and hence depend on the electron density and temperature.

Error ranges vary between parameters. The electron and ion number densities and the spacecraft potential have an inherent error of $< 10\%$; the electron and ion temperatures $< 20\%$ [42].

---

3 Determined empirically from LP and CAPS/ELS cross-calibrations.
If the LP is exposed to sunlight, as is often the case, it emits photoelectrons that add to the total current, according to

\[ I = I_e + I_i + I_{ph}. \] (4.13)

In Titan’s dense ionosphere the electron and ion currents are much larger than the photoelectron current and hence dominate the total current. However, for more tenuous plasmas, the photoelectron current can contribute significantly and has to be taken into account.

The LP measurements are analysed by fitting the data to the above equations. The relation between the sampled currents and the bias potential applied to the probe can be displayed as a typical current-voltage curve, shown in Figure 4.3. As seen in the figure, the relationship is linear for high positive and negative values of the bias voltage.

![Figure 4.3: The current-voltage characteristics of a sweep from flyby T18 with two electron populations. LP data are shown as blue dots. Superposed are the theoretical fits of the ion current (red dot-dashed line), two electron currents (green line and green dashed line, respectively), and the total current (red line). The x-axis shows applied bias voltage on the probe. Adapted from Paper II.](image)

While the above description gave a brief introduction to the use of the LP onboard Cassini, full treatment requires a more rigorous theory; see, e.g., [57].

40
Upper hybrid emissions
In the close vicinity of Titan the electric antennas measure a series of narrow-band electric field emissions, known as the upper hybrid emissions. The upper hybrid resonance is an electrostatic resonance which occurs at

\[ f_{\text{UH}} = \sqrt{f_{\text{ge}}^2 + f_{\text{pe}}^2} \]  

(4.14)

where

\[ f_{\text{pe}} = \frac{1}{2\pi} \sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}} \]  

(4.15)

is the electron plasma frequency, and

\[ f_{\text{ge}} = \frac{eB}{m_e 2\pi} \]  

(4.16)

is the electron gyro frequency. For Titan flybys, \( f_{\text{pe}} \gg f_{\text{ge}} \), meaning that Equation 4.14 may be simplified into

\[ f_{\text{UH}} \approx f_{\text{pe}}. \]  

(4.17)

This allows us to derive the electron density from the upper hybrid measurements and to compare the results to those of the LP. However, for some Titan flybys, two emission lines are found, and for others no obvious plasma line is detected, which of course complicates comparisons between the two measurement methods.

4.1.2 Other instruments employed

Cassini plasma spectrometer
CAPS explores plasma within Saturn’s magnetosphere [58]. The instrument collects information about the composition, density, flow, velocity and temperature of the ions and electrons. CAPS consists of three different sensors: an ion mass spectrometer (IMS), an ion beam spectrometer (IBS), and an electron spectrometer (ELS), the latter of which has contributed to the work in this thesis.

ELS is a 'top-hat' electrostatic analyser with an energy per charge \((E/q)\) range for negatively charged particles of 0.6 - 28000 eV/q. The angular range of the instrument is \(160^\circ \times 5^\circ\) divided into eight \(20^\circ \times 5^\circ\) pixels. ELS was constructed to measure electrons, but is now also used to measure negative ions [12, 13].

Ion and neutral mass spectrometer
INMS is a quadrupole mass spectrometer designed to measure neutral species and low-energy ions [54]. The instrument determines the composition and
structure of positive ions and neutral particles. It is able to determine the chemical, elemental and isotopic composition of the gaseous and volatile components of the neutral particles, as well as the low energy ions in Titan’s atmosphere and ionosphere. The INMS can be operated in three different modes: a closed source neutral mode, suitable for the measurement of non-reactive neutrals; an open source neutral mode, for reactive neutrals; and an open source ion mode, for ions with energies less than 100 eV. The instrument has a mass range of 1 - 99 amu. Measurements by the INMS are sensitive to changes in spacecraft potential and the ram flow direction. For this reason, the INMS is only operated during certain flybys.

**Magnetometer**

The magnetometer onboard Cassini measures the magnitude and direction of the magnetic field. MAG is a fluxgate magnetometer that supplies vector components of the magnetic field [21].

For more information on the various instrument packages, see [2].
5. Discussion and outlook

In this thesis, we study the ionosphere of Titan during flybys with closest approaches of around 1000 km above ground. In this altitude region, we show that solar photons are the main ionisation source on the dayside, but also that impacting magnetospheric electrons are important for the ionisation on the nightside and in the transition region. Furthermore, we show that the ionosphere at these altitudes is the scene of some very complex chemical reactions, with heavy positive as well as heavy negative ions involved, and that there are measurable currents flowing in Titan’s ionosphere, possibly connecting to Saturn’s magnetosphere. For a discussion of the various assumptions used, the discrepancies between the model and observations, and the accuracy of the results, please refer to the articles.

In this Chapter we discuss the possible implications of the findings for the formation of haze on Titan.

5.1 Titan’s organic haze

Already during the passage of Voyager I and the very early flybys by Cassini, it was established that Titan is surrounded by an orange haze. More recent measurements by Cassini have shown that the haze around the moon is divided into two parts; a main haze layer, reaching from the ground up to approximately 300 km, and a detached haze layer, found between 500 and 600 km altitude [29]. Figure 5.1 shows the main and detached haze layers as seen by the narrow angle camera onboard Cassini.

The Titan haze is believed to consist of neutral particles of the order of a few tens of nanometers, possibly even larger, often referred to as either aerosols or tholins [36, 56]. The haze is an interesting subject for study, given suggestions that a similar haze layer may have existed on the primitive Earth. Experiments performed under conditions likely to resemble those on the early Earth indicate that the aerosol production on our planet may have been of the order of $10^{14}$ g year$^{-1}$. If this value is correct, an organic haze at Earth could have served as a primary source of organic material to the surface [48].

Although the haze layers on Titan were identified a long time ago, there is still an ongoing discussion of their origin. There are two main hypotheses regarding how and where the haze is created, as will be discussed in the following section.
5.2 Haze formation mechanisms

The Titan haze is thought to originate either in the stratospheric region, at an altitude of around 1000 km, or in the thermospheric region, at altitudes below 550 km.

5.2.1 Stratospheric sources

As discussed in Chapter 3, the fact that the positions of the haze layers coincide with peaks in electron density caused by precipitating ions and cosmic rays points towards the interpretation that the haze is created by recombination of the resulting ions in these processes [29]. In an alternative model, it has been suggested that the aerosol production in the stratosphere is driven by absorption of solar far-ultraviolet (FUV) radiation [23]. What both hypotheses have in common is the conclusion that the haze is mainly created at the altitudes where it has been detected.

5.2.2 Thermospheric sources

Contrary to the idea of the haze being formed at similar altitudes to where it is observed, it may also be conceived that thermospheric sources act at higher altitudes to create aerosols that diffuse downwards before appearing...
as haze. The aerosol formation is in this case believed to start with the formation of negative ions, positive ions, or a combination of the two. Early ideas on aerosol formation based on Cassini measurements were presented by Waite et al. [56], who suggested that ion-neutral chemistry at altitudes around 1000 km plays a major role in the formation of the Titan haze. When ionised, the most abundant atmospheric constituents, N$_2$ and CH$_4$, combine through a number of reaction pathways to form benzene, C$_6$H$_6$, and other complex organics. In the next step, these evolve to negatively charged organic ions and further to tholins that would later "rain down" through the ionosphere to form the haze layers at lower altitudes. Figure 5.2 shows a cartoon describing this process.

![Diagram](image.png)

**Figure 5.2:** Cartoon showing the chemical processes leading to tholin formation in Titan’s upper atmosphere. Image credit: Hunter Waite/SWRI.

Wahlund et al. [53] chose to focus on the heavy positive ions detected at similar altitudes (around 1000 km) as a starting point for aerosol formation, whereas a model by Vuitton et al. [50], including negative ion chemistry, suggests that negative ions act as precursors to the observed aerosols. Recent
theoretical work also points towards the conclusion that the haze is, indeed, a result of thermospheric chemistry; see e.g., [37, 47].

5.3 Our contribution

The findings presented in this thesis support the theory that the tholins originate in the thermosphere and later diffuse down through the ionosphere.\(^1\) In Papers I and II, we show that the ionisation rates in the deep ionosphere of Titan (around 1000 km) are high, and that both solar EUV radiation and ionisation by incoming magnetospheric electrons are important for the creation of an ionosphere around the moon.

In Paper III, we detect currents in Titan’s ionosphere of the order of 10 to 100 nA m\(^{-2}\). We believe that these currents might be driven by a cross tail electric field in the wake of Titan, caused by the draping of Saturn’s magnetic field. E.g., joule heating associated with the currents could possibly be a driver for the chemical reactions responsible for haze formation. Heating of the electrons would imply slower recombination times, which might lead to an accumulation of heavy ions.

In Paper IV, we measure the negative ion abundance during the deepest Titan flyby performed to date, and come to the conclusion that the ions are either more abundant or moving at a higher velocity than previously thought. By adding a negative ion component to the analysis, we achieve several good fits to the data, as long as the imposed negative ion flux is kept constant. In the paper, we describe two limiting cases and conclude that negative ions are present in considerable amounts, with densities ranging from around 1000 to more than 10 000 cm\(^{-3}/Z\). The ions move at velocities between a few hundred m s\(^{-1}\) and a few km s\(^{-1}\). A large number of (possibly negatively charged) aerosol particles are expected at these altitudes, as indicated by a theoretical study [36]. This study is also consistent with the observed negative ion population at higher altitudes [13, 36].

After the paper was submitted, we have continued our work on the negative ions. Depending on the amount of negative ions relative to the electrons, we might draw some further conclusions. If the negative ions are abundant (similar or higher concentrations than the electrons) and on average more massive than the positive ions, it could be argued that they should fall deeper into the atmosphere than the positive ions. This would produce an ambipolar electric field striving to restore charge neutrality, which in turn could have the effect of dragging positive ions towards Titan and restraining negative ions from falling further. By considering the balance between the production and loss rates of the negatively charged particles (including both ions and electrons) one finds that negative ion densities higher than 10 000 cm\(^{-3}/Z\) are rather unlikely to

\(^1\)However, the haze may still be due to a combination of stratospheric and thermospheric sources.
occur in Titan’s deep ionosphere. Indeed, even if we assume a strong contribution to the electron production rate by ion precipitation at these altitudes, we cannot easily obtain such high densities while still keeping the reaction coefficients at reasonable values [24, 49]. More work is needed, however, before we can draw any firm conclusions.

5.4 Unknowns

Although much effort has been put into trying to work out the chemical pathways leading to the formation of tholins, there is still a lack of understanding of what chemical processes are responsible for this. At the moment we lack information on several aspects of the formation, such as:

**Detailed ion chemistry**

Due to limitations of the INMS, we cannot make detailed measurements of the ions above 100 amu. However, as shown in Chapter 3, there exists a substantial amount of heavy ions at deep altitudes in Titan’s ionosphere. Furthermore, the INMS only measures the neutrals and positive ions. For negative ions we need to rely on the electron spectrometer and the LP, neither of which is able to provide sufficient mass resolution to identify individual ion species.

**The agnostosphere**

The region in Titan’s ionosphere between 400 km and 900 km, sometimes called the *agnostosphere*, is poorly characterised as it falls between the thermosphere, which is probed during the Titan flybys, and the stratosphere, which is probed primarily by observations of thermal infrared emissions [34].

**Negative ions**

The negative ions detected by the CAPS/ELS are given in mass per charge. Having double, triple or even higher orders of charge of the particles would thus imply correspondingly heavier ions, which of course would need to be taken into account in the models. This would also influence the interpretation of our own observations, since we derive the density per charge of the negative ion population.

**Ionisation sources**

The relative importance of the various ionisation sources is still under debate. It is generally accepted that solar photon ionisation is the driver of the main ionospheric peak on the dayside, but regarding the ionisation at lower altitudes, as well as on the nightside, more investigations are necessary.
Recombination coefficients

A key issue in the modelling of Titan’s ionosphere is which values to assign to the recombination coefficients of both positive and negative ions, as they describe the lifetime of the ions. Laboratory measurements of rate coefficients for the reaction between positive and negative ions (leading to neutral products) is needed for a deeper insight into the ion chemistry acting in Titan’s deep ionosphere [28, 49].

5.5 Outlook

Given the limitations of the instrumentation onboard Cassini discussed in the preceding section, it will of course be very interesting to see the results from a future spacecraft with improved equipment that would pass by, or even better, orbit, Titan. However, this lies many years ahead. In the meantime, we can increase our knowledge by looking in depth at the existing datasets from Cassini, as well as analysing the new data that are continuously being transmitted back to Earth. To make progress in the study of haze formation at Titan, we need to deepen our understanding of the ionospheric composition. Now that the LP has been able to confirm the detection of negative ions by the ELS, the two datasets may be combined in order to achieve a better estimate of the negative ion density, which up until now has been very rough. The same applies for the positive ion density. Data from the LP, together with the combined INMS and IBS measurements, could be used to better determine the amount of heavy positive ions, as well as the ion drift velocity. More work is needed on finding out which ionisation sources are effective at various altitudes, and also in order to establish the interrelation between these ionisation sources. This is crucial to set bounds for what chemistry is possible. Finally, important work is yet to be carried out on the energy transport issue. Without mentioning individual instruments, I think the Cassini society ought to dedicate more time to try and understand how energy is transported in the ionosphere; via currents, collisions, heating, etc. Ultimately, such studies could lead to a better understanding of how the energy deposition influences the chemical reactions and hence the formation of aerosols.

In short, although much important work has been carried out to understand the creation, structure and dynamics of Titan’s ionosphere, there are no doubt many substantial discoveries yet to be made.
6. Summary of papers

Here follows a short summary of all papers included in the thesis, together with a description of the contribution made by the author of this thesis to each publication.

Paper I

On magnetospheric electron impact ionisation and dynamics in Titan’s ram-side and polar ionosphere - a Cassini case study

Published in Annales Geophysicae, 2007

In this paper, we conduct a case study of the sixth Titan flyby, T5, focusing on the outbound leg that occurred on the nightside of the moon. From RPWS/LP observations, we conclude that an important region for the interaction between Saturn’s magnetosphere and Titan’s ionosphere is the exo-ionosphere. The exo-ionosphere is the region above the ionosphere, where the plasma density decreases exponentially until a drop to magnetospheric values is detected. Moreover, we use a simplified ionospheric model, based on measurements of the neutral density by the INMS and the incoming electron spectrum by the CAPS/ELS, to provide estimates of the ion and electron densities. By comparing the modelled and measured densities, we conclude that impacting magnetospheric electrons can account for the observed ionospheric density profile of this flyby.

My contribution: I constructed the ionospheric model and compared it to data. I wrote half of the text.

Paper II

On the ionospheric structure of Titan

Published in Planetary Space Science, 2009

This paper is a statistical study based on 17 Titan flybys. As each flyby consists of two legs – inbound and outbound – this adds up to a total of 34 altitude profiles. We use these profiles to study the solar zenith angle (SZA) dependence of the electron number density and electron temperature at the
ionospheric peak, and come to the conclusion that solar photons are the main ionisation source of Titan’s dayside atmosphere, which showed on average 3 - 5 times more plasma than the nightside. Typical plasma densities were found to be 2500 - 3500 cm$^{-3}$ and 400 - 100 cm$^{-3}$, respectively. Between dayside and nightside, a broad transition region between SZA 50 - 100 degrees was identified and interpreted as a result of Titan’s extended atmosphere. Electron temperatures were found to be 0.03 - 0.06 eV, independent of SZA. The conclusion from Paper I, i.e., that magnetospheric impacting electrons alone can account for the observed ionospheric density profile, is not contradicted by this more comprehensive study of nightside flybys.

My contribution: I performed the data analysis together with the co-authors. I planned and carried out the study. I wrote the text.

Paper III
Detection of currents and associated electric fields in Titan’s ionosphere from Cassini data
Published in Journal of Geophysical Research, 2011

The work leading up to this paper was conducted during a stay as a visiting PhD student at the University of Leicester, UK; an opportunity, which opened up for a multi-instrument study of Titan’s deep ionosphere, using the LP, the magnetometer and the electron spectrometer. Following a paper by Rosenqvist et al. [44], we had good reasons to believe that detectable currents were flowing in Titan’s ionosphere. We therefore combined cold plasma and magnetic field measurements with the conductivity estimates from [44]. This allowed us to detect currents of the order of 10 to 100 nA m$^{-2}$, with associated electric fields of a few $\mu$V m$^{-1}$. The currents principally flow in two directions; perpendicular to the magnetic field; and perpendicular to both the magnetic and electric fields. This was the first observation of ionospheric currents at Titan.

My contribution: I planned the study from existing data sets together with the co-authors. I carried out the study. I wrote the text.

Paper IV
Detection of negative ions in the deep ionosphere of Titan during the Cassini flyby T70
Accepted for publication in Geophysical Research Letters, 2012

Paper IV is again a case study, this time of flyby T70, the deepest Titan flyby of the whole mission. It had a closest approach of 880 km, which is approximately 70 km deeper than what had previously been achieved. During T70,
we were able to detect a substantial amount of negative ions solely by using
the LP. As the addition of a negative ion component to the analysis increased
the number of free variables, we were able to achieve several possible fits to
the data. Nevertheless, the measurements could not be explained without the
addition of a negative ion current. In the paper, we show that the negative ion
density below 900 km is in the range of around 1000 up to more than 10 000
\(\text{cm}^{-3}/\text{Z}\), and that the ion velocity is at least a few hundred \(\text{m s}^{-1}\), and possi-
bly as high as a few km \(\text{s}^{-1}\). Our results in Paper IV confirm the findings of
Coates et al. [12], who first detected negative ions in Titan’s ionosphere.

My contribution: I planned the study and performed the data analysis to-
gether with the co-authors. I carried out the study. I wrote the text.


7. Sammanfattning på svenska
Langmuirproben och använda resultaten till att öka förståelsen för hur Titans jonosfär bildas, vad som påverkas dess struktur samt vilka beståndsdelar den har.


Artikel II är en statistisk studie av 17 förbiflygningar där vi undersöker hur zenitvinkeln påverkar jonosfärens uppkomst och struktur. Zenitvinkeln anger var mätningarna gjorts i förhållande till solen. En zenitvinkel på 0 grader betyder att vi befinner oss rakt under solen, medan en zenitvinkel på 180 grader visar att vi är på helt motsatt sidan av månen; det vill säga på nattsidan. Våra resultat visar att Titans jonosfär på dagsidan är i genomsnitt fyra gånger så tätt som den på nattsidan – typiska densiteter är 2500 - 3500 cm\(^{-3}\) för dagsidan och 400 - 1000 cm\(^{-3}\) för nattsidan. Vi konstaterar också att höjden där elektrontätheten når sitt maximum blir lägre ju lägre zenitvinkeln är. Från detta kan vi dra slutsatsen att solen är den viktigaste jonisationskällan för Titans dagsida. Då våra mätningar påvisade ett tätt plasma även på månens nattsida, långt ifrån solstrålningens påverkan, kan vi konstatera att inkommande partiklar från Saturnus magnetosfär också bidrar till den totala jonisationen, i överensstämmelse med slutsatsen i Artikel I.

Artikel III är en omfattande studie baserad på data från tre av instrumenten ombord på Cassini. Förutom Langmuirproben har vi använt oss av en magnetometer (som mäter magnetfält) och en elektronspektrometer (som mäter högenergetiska elektroner och negativa joner). Genom att kombinera mätningar från främst Langmuirproben och magnetometern kan vi beräkna de strömmar som flyter i Titans jonosfär. Dessa strömmar hade inte påvisats tidigare, men de förväntades finnas eftersom beräkningar visat att Titans jonosfär är ledande, det vill säga har möjlighet att transporterar elektrisk laddning i form av strömmar. I artikeln koncentrerar vi oss på tre förbiflygningar av Titan; T18, T20 och T21. Dessa var de enda i urvalet som hade liknande magnetfältssignaturer före och efter månpassagen, vilket är nödvändigt för att vi ska

\(^{1}\) Ingen logik där inte.
kunna särskilja hur strömmarna i jonosfären påverkar det uppmäta magnetfället. För samtliga dessa förbiflygningar kan vi påvisa strömmar i storleksordningen 10 - 100 nA m$^{-2}$. Detta är första gången som strömmar observerats i Titans jonosfär.

I Artikel IV har vi återigen koncentrerat oss på en förbiflygning; i det här fallet T70. T70 är den djupaste passage av Titan som har ägt rum – som närmast flög Cassini bara 880 km från månens yta. Redan i ett tidigt skede av dataanalysen kunde vi se att T70 särskiljde sig från de tidigare förbiflygningarna eftersom vi inte kunde få goda anpassningar till data utan att också addera en ström av negativa joner. Negativa joner hade tidigare uppmätts av elektronspektrometern, men detta var första gången som deras mätningar kunde bekräftas av ett annat instrument. Något oväntat visade sig dessa joner vara mycket fler och/eller färdas med högre hastighet än vad som förväntades. Enligt vår uppskattning har de negativa jonerna en densitet mellan ungefär 1000 cm$^{-3}$ och 10 000 cm$^{-3}$ och färdas med hastigheter från några hundra m s$^{-1}$ upp till några km s$^{-1}$. Detta betyder att de kemiska modeller som gjorts av Titans jonosfär kan komma att behöva revideras.

Innan Cassini kom fram till Titan visste man inte mycket alls om denna Saturnus största måne. Tidigare förbiflygningar av Voyager och Pioneer hade avslöjat att Titan hade en jonosfär, men hur den var uppbyggd och vad den bestod av var okänt. Genom vår forskning har vi kunnat bidra till en ökad kunskap om jonosfärens tillkomst (Artikel I och II) och struktur (Artikel II och III), samt även bidragit med en pusselbit (Artikel IV) till det miljonbitarspussel som håller på byggas för att beskriva vad Titans jonosfär består av.
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Ad ranis omnibus

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Nuww jer he slut, nuww hav i klart
Nuww val he eint na meir

A he som eint ha vorte gjort
He lämmen ve deill senn


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