Photoionisation and
Spacecraft-Shadow Interactions in
Saturn’s Inner Magnetosphere

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I, Sam A. Taylor, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the work.
Abstract

In this thesis, data analysis and modelling techniques are used to study the impact of solarillumination on the plasma and neutral molecules in Saturn’s inner magnetosphere. The data used are from the Cassini spacecraft, a joint NASA-ESA-ASI flagship mission to explore the Saturn system.

The first study focuses on photoelectron observations by the CAPS-ELS instrument at Saturn’s icy moon Enceladus. The geometry of each flyby is analysed and encounters are selected for suitability for observing photoelectrons originating in Enceladus neutral plume material. Fitting techniques are used to subtract the background thermal electron population, revealing characteristic photoelectron spectra and several previously unidentified peaks. A photoelectron model is adapted to create a synthetic production spectra of photoelectrons in the plume. Comparison between the subtracted electron spectra and the model verifies that the observed peak structure can be entirely explained by the photoionisation of plume neutrals.

The second study investigates the effects of eclipsing by Saturn on the photoelectron population in the neutral torus. Despite the photoionisation source being obscured, during several shadowing events characteristic photoelectron signatures are observed throughout. This unexpected observation leads us to conclude that there must be a transport process delivering photoelectrons into the shadow. A detailed model is developed to show the geometry of each event including: shadow geometry, spacecraft trajectory, simple magnetic field model and a neutral density model. Analysis of this model suggests that photoelectrons are being produced in the neutral torus of Saturn and transported along field lines deep into the shadow of Saturn.
Finally, the effects of shadowing on the spacecraft are investigated. The sudden loss of illumination appears to affect both the local plasma as photoionisation of neutrals is switched off and the spacecraft itself in the form of rapid spacecraft potential changes. Along with spacecraft effects, there is also evidence of electron density drops inside the shadow, likely due to the removal of photoionisation as a plasma source in darkness.
Impact Statement

The research presented in this thesis is primarily of academic interest, particularly in the field of space plasma physics. For example, Chapter 3 contains research published in the *Journal of Geophysical Research: Space Physics*, one of the leading research journals in the field.

This research contributes to the ever growing body of knowledge about the Saturn system, especially its inner magnetospheric region. Although the Cassini mission has come to an end, the techniques and results presented in this thesis may inform future research using the wealth of data gathered by the spacecraft during its 20 year mission. Along with future studies on Saturn, this study may provide context and background for research on the other magnetospheres of the Solar System. The knowledge and understanding gained at Saturn is already being used to help understand the magnetosphere of Jupiter with the Juno spacecraft and will no doubt be of use in coming decades when spacecraft visit Neptune and Uranus.
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Chapter 1

Introduction

Mosaic image of Saturn from Cassini. Composition credit: Mattias Malmer, Image data: Cassini Imaging Team.

This introductory chapter covers the basic concepts in space plasma physics, their application to planetary magnetospheres and introduces Saturn’s magnetospheric environment. Many of the descriptions of space plasma concepts in this chapter are based on material found in Kivelson and Russell [1995] and Baumjohann and Treumann [1996].
1.1 Plasma Physics Concepts

1.1.1 Space Plasmas

A plasma is a gas of ionised (positive and negative) particles which are ‘free’ to interact with and influence the local electric and magnetic fields. Plasmas contain roughly the same number of electrons and ions and so despite being comprised of charged particles they can be considered neutral on macroscopic scales. Plasmas are rarely found near the Earth’s surface, but are common in the solar system and make up more than 99% of all known visible matter in the universe.

In order for an ionised gas to be considered a plasma, it must satisfy three criteria: the Quasi-neutrality condition, the Collective behaviour condition and the Collision condition. These will be introduced in context throughout this introduction section.

Quasi-Neutrality Condition

Charged particles are influenced by surrounding electric and magnetic fields and produce electric fields themselves. The potential of the field produced by a charged particle at a distance \( r \) is described by the electric potential (or Coulomb potential), \( V_E \)

\[
V_E = \frac{q}{4\pi \varepsilon_0 r} \quad (1.1)
\]

\( q \) - particle charge \quad \varepsilon_0 \) - permittivity of free space

Plasmas may be considered quasi-neutral because if a charged particle enters a plasma, other charged particles in the plasma will move to ‘shield’ the extra charge and restore neutrality. The potential of a plasma is described by

\[
\Phi_D = \frac{q}{4\pi \varepsilon_0 r} \exp\left(-\frac{r}{\lambda_D}\right) \quad (1.2)
\]

Where \( \lambda_D \) is known as the Debye length. It is the scale over which electrons screen out electric fields in plasmas, this means that significant charge separations can only occur
1.1. PLASMA PHYSICS CONCEPTS

at distances greater than

\[
\lambda_D = \sqrt{\frac{\varepsilon_0 k_B T_e}{n_e e^2}} \tag{1.3}
\]

\(k_B\) - Bolzmann constant  \(n_e\) - electron density  
\(T_e\) - electron temperature  \(e\) - electron charge

This leads us to the first plasma condition, the Quasi-neutrality condition, which states that a plasma can be considered quasi-neutral only at length scales, \(L\), much greater than the Debye length.

\[
L \gg \lambda_D \tag{1.4}
\]

Collective Behaviour Condition

Another useful construct to consider is the Debye sphere, which is simply a sphere with a radius of the Debye length. The Collective behaviour condition is satisfied when there is sufficient charged particle density for each individual charge to be shielded by many others. This occurs when the number of charged particles within the Debye sphere, \(N_D\), is large

\[
N_D = 4 \frac{\pi}{3} \lambda_D^3 n_e \gg 1 \tag{1.5}
\]

Collision Condition

Particles in a plasma respond to perturbations caused by external forces by moving. Electrons however are less massive and therefore more mobile than the ions, this causes the electrons to oscillate about the ions at the plasma frequency, \(\omega_{pe}\)

\[
\omega_{pe} = \sqrt{\frac{n_e e^2}{m_e \varepsilon_0}} \tag{1.6}
\]

\(m_e\) - electron mass

This quantity leads to the third plasma condition, the collision condition which states that the average time between electron-neutral collisions \(\tau_n\) must be larger than the
reciprocal of the plasma frequency $\omega_{pe}$

Collision Condition 

$$\omega_{pe} \tau_n \gg 1$$  \hfill (1.7)

### 1.1.2 Single Particle Motion

Fully describing the dynamics of a plasma is complex due to the electromagnetic interaction between every charged particle. Each charged particle interacts with the electromagnetic fields of every other charged particle in addition to any external fields. This section describes some of the approaches used to understand the plasma dynamics observed in nature.

### Maxwell’s Equations

Maxwell’s equations form much of the basis for describing the electric field $E$ and magnetic field $B$ components of the electromagnetic force:

$$\nabla \times E = -\frac{\partial B}{\partial t}$$  \hfill (1.8)

$$\nabla \times B = \mu_0 \left( J + \varepsilon_0 \frac{\partial E}{\partial t} \right)$$  \hfill (1.9)

$$\nabla \cdot E = \frac{\rho_q}{\varepsilon_0}$$  \hfill (1.10)

$$\nabla \cdot B = 0$$  \hfill (1.11)

**Universal constants**

- $\varepsilon_0$ - permittivity of free space
- $\mu_0$ - permeability of free space

**Sources**

- $J$ - electric current density
- $\rho_q$ - electric charge density

### 1.1.2.1 Single Particle Motion

A charged particle with charge $q$ moving at a velocity $v$ in the presence of an electric field $E$ and a magnetic field $B$ will experience a force $F$ as described by the Lorentz force.

$$F_L = q [E + (v \times B)]$$  \hfill (1.12)

Therefore the basic equation of motion for a charged particle of mass $m$ in an electric
and magnetic field becomes

\[ m \frac{dv}{dt} = q \left[ E + (v \times B) \right] \]  

(1.13)

**Gyromotion**

First we consider charged particle motion in a uniform, steady magnetic field \( B \) and no electric field. Rewriting Equation 1.13 where \( E = 0 \) gives

\[ m \frac{dv}{dt} = qv \times B \]  

(1.14)

The force felt by the particle is perpendicular to both \( v \) and \( B \) and so the magnetic field does no work on the particle and the kinetic energy of the particle must remain constant. It follows that the velocity can only change in direction and so the particle moves in a circle perpendicular to \( B \) at a constant speed. Any velocity the particle has parallel to \( B \) remains constant and so in general, a charged particle’s motion in a uniform \( B \) is helical with angular frequency \( \Omega_G \), known as the **gyrofrequency**.

\[ \Omega_G = \frac{qB}{m} \]  

(1.15)

The radius of the circular path the particle follows is called the **gyroradius**, \( r_G \) and increases as the particle’s velocity perpendicular to \( B \) increases.

\[ r_G = \frac{mv_\perp}{qB} \]  

(1.16)

This gyromotion is illustrated in Figure 1.1.
Any velocity component parallel to the magnetic field remains unaffected and the travelling charged particle will follow a helical motion along the magnetic field direction (Figure 1.2). From this motion a useful property called the pitch angle $\alpha$ is defined as the angle between the particle’s velocity vector and the local magnetic field. Therefore, pitch angle is given by

$$\alpha = \tan^{-1}\left(\frac{v_\perp}{v_\parallel}\right)$$  

$v_\perp$ - Velocity perpendicular to $B$  
$v_\parallel$ - Velocity parallel to $B$
1.1.2.2 Electric Drift

Now we consider the additional effects of a uniform steady electric field $E$. Any parallel electric field will be cancelled by the mobile electrons and ions, however perpendicular components of the electric field will exert a force on the charged particles. The electric field causes the guiding centres of the particles to drift perpendicular to $B$ and $E$ via the $E \times B$ drift.

$$E \times B \text{ Drift} \\
\mathbf{v}_D = \frac{E \times B}{B^2}$$

This results in a drift motion which is independent of charged particle mass and charge and all particle species drift in the same direction at the same velocity as illustrated in Figure 1.3

![Image](image.png)

**Figure 1.3:** $E \times B$ drift in uniform, steady magnetic and electric fields. Figure from *Kivelson* [1995].

1.1.2.3 Magnetic Drift

Magnetic fields in the solar system are not uniform, they have curved field lines and strength gradients. We will first consider the effects of curved field lines.
Curvature Drift

As a charged particle travels along a curved field line, it feels a centrifugal force outwards from the centre of curvature of the field as illustrated in Figure 1.4. This leads to *curvature drift* given by

\[
\mathbf{v}_c = \frac{mv_{\parallel}^2}{q} \frac{\mathbf{R}_c \times \mathbf{B}}{R_c^2 B^2}
\]  

(1.19)

*Figure 1.4:* Particle motion in a curved magnetic field \( \mathbf{B} \). The particle feels a centrifugal force \( \mathbf{F}_R \) in the direction of the radius of curvature of the field \( \mathbf{R}_c \). \( \mathbf{v}_{\text{di}} \) indicates the ion drift velocity direction (electrons drift in the opposite direction). Figure adapted from Baumjohann and Treumann [1996].

Gradient Drift

Next we consider a magnetic field in which there is a gradient in magnetic field strength perpendicular to \( \mathbf{B} \). As a charged particle orbits its guiding centre, any change in the strength of \( \mathbf{B} \) will change the size of the gyroradius (Equation 1.16) and cause a drift perpendicular to \( \mathbf{B} \) and \( \nabla \mathbf{B} \) as illustrated in Figure 1.5. The drift experienced by the particle is described by

\[
\mathbf{v}_\nabla = \frac{mv_{\parallel}^2}{2qB^3} (\mathbf{B} \times \nabla \mathbf{B})
\]  

(1.20)
It should be noted that both curvature and gradient drifts are dependent on charge and so electrons and ions will drift in opposite directions which set up currents. They also depend on particle velocity and so are especially important for high energy particles.

1.1.2.4 Adiabatic Invariants

An adiabatic invariant is considered to be a quantity which remains essentially constant in a slowly changing environment compared to a given oscillatory period. There are three invariants relating to the motion of charged particles in electromagnetic fields.

First Adiabatic Invariant: Magnetic Moment

The first adiabatic invariant is the magnetic moment, given by

\[
\mu = \frac{mv_{\perp}^2}{2B} = \text{constant}
\]

(1.21)

The implication of this is that as a charged particle moves along a magnetic field line with increasing field strength, it will reach a point where the \(v_{\parallel}\) decreases to zero (while \(v_{\perp}\) increases) before reversing direction and being reflected. This is known as magnetic mirroring where the point of reflection is called the mirror point.
The motion of a charged particle in a converging field is governed by two constants:

\[
|v| = \text{constant} \quad (1.22) \\
\frac{\sin^2 \alpha}{B} = \text{constant} \quad (1.23)
\]

The mirror point can be easily described by inserting \( \alpha = 90^\circ \) into Equation 1.23.

\[
\frac{\sin^2 \alpha}{B} = \frac{\sin^2 90^\circ}{B_m} = \frac{1}{B_m} \quad (1.24)
\]

\[
\therefore B_m = \frac{B}{\sin^2 \alpha} \quad (1.25)
\]

It is important to note that the mirror point is dependent only on pitch angle \( \alpha \) and not on the energy or type of particle (electron or ion). Particles which are more field aligned (small \( \alpha \)) mirror at higher magnetic field strengths than less field aligned (large \( \alpha \)) particles. The mirroring of a charged particle is illustrated in Figure 1.6.

**Figure 1.6:** Particle gyromotion and mirroring in a converging magnetic field. Figure from *Baumjohann and Treumann* [1996].
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Second Adiabatic Invariant: Longitudinal Invariant

In a dipolar field, magnetic field lines converge at each magnetic pole. A charged particle moving in this converging field will be reflected at the mirror point (Equation 1.25), oscillating at a bounce frequency \( \omega_b \). The longitudinal invariant is defined as

\[
\text{Longitudinal Invariant} \quad J = \oint_V m v_\parallel ds = \text{constant} \quad (1.26)
\]

\( ds \) - element of guiding centre path

The invariant holds constant for electromagnetic field changes with \( \omega \ll \omega_b \).

Third Adiabatic Invariant: Drift Invariant

The third invariant is called the drift invariant \( \phi \) and is defined as the magnetic flux enclosed by a charged particle completing a full drift orbit.

\[
\text{Drift Invariant} \quad \phi = \frac{2\pi m}{q^2} M = \text{constant} \quad (1.27)
\]

\( M \) - magnetic moment of the axisymmetric field

1.1.3 Collective Behaviour

On the macroscopic scale, the many charged particles present in space plasmas exhibit a form of collective behaviour due to constant inter-particle interactions. Each charged particle in a plasma generates its own electric field (as a point charge) and magnetic field (as it moves) while simultaneously reacting to the electromagnetic fields of all surrounding particles. The most accurate way to describe the state of a plasma would be to record the fields at every position and the position and velocity of every particle. Although space plasmas have very low densities, there are still many more particles than could realistically be accounted for in such a direct approach.
1.1.3.1 Kinetic Theory

Kinetic theory provides a statistical description of all the charged particles in each species by representing the particle as a probability distribution function of the form $f_i(x, v, t)$, where $i$ is the particle species, $x$ is the position of the particle, $v$ is the velocity and $t$ is time. The evolution of this distribution function (for a collisionless plasma) is described by the Vlasov Equation,

\[
\frac{\partial f_i}{\partial t} + v \cdot \nabla_x f_i + \frac{F_L}{m_i} \cdot \frac{\partial f_i}{\partial v} = 0 \quad (1.28)
\]

$F_L$ - Lorentz Force (Equation 1.12) 
$m_i$ - mass of particle species $i$

Maxwellian Distribution

Commonly, the velocity distribution for a collisionless plasma in equilibrium is given by the Maxwellian Distribution. A plasma described by a Maxwellian is in thermal equilibrium with no energy exchange processes. The Maxwellian for a particle species $i$ is given by

\[
f_i(v) = n_i \left(\frac{m_i}{2\pi k_B T_i}\right)^{3/2} \exp\left(-\frac{m_i v^2}{k_B T_i}\right) \quad (1.29)
\]

$n_i$ - number density of species $i$ 
$T_i$ - temperature of species $i$ 
$m_i$ - mass of species $i$ 
$v$ - velocity 
$k_B$ - Boltzmann constant

Kappa Distribution

Maxwellian distributions are often not sufficient to fully describe observed space plasmas as they are rarely in true thermal equilibrium. Since Vasyliunas [1968], a modified Maxwellian distribution called a Kappa Distribution has been frequently used instead to model observed distributions throughout the solar system (Livadiotis and McComas [2013] and references therein). For example, there are two distinct electron populations observed in Saturn’s inner magnetosphere which are often modelled using two Kappa distributions [Schippers et al., 2008; Livi et al., 2014].
1.1. PLASMA PHYSICS CONCEPTS

The Kappa distribution is what’s known as a power law distribution and deviates significantly from a Maxwellian at high energies (see Figure 1.7) and is given by [Vasyliūnas, 1968]

\[
Kappa Distribution \quad f(v) = \frac{N}{\omega_0^3} \frac{\Gamma(\kappa + 1)}{(\pi \kappa)^{3/2}} \frac{1}{\Gamma(\kappa - \frac{1}{2})} \left(1 + \frac{v^2}{\kappa \omega_0^2}\right)^{-\kappa+1} 
\]

\(N\) - total number density \hspace{1cm} \(\Gamma\) - incomplete gamma function
\(\kappa\) - exponent at high energies \hspace{1cm} \(\omega_0\) - most probable speed

Kappa distributions become Maxwellian as \(\kappa \rightarrow \infty\).

**Magnetohydrodynamics (MHD)**

Alternatively, it is also possible to describe the plasma as a conducting fluid by combining the Navier—Stokes fluid equations with Maxwell’s equations. The resulting equations are called the *Magnetohydrodynamics (MHD) Equations* and can be formulated for a single particle species or multiple species. MHD is a macroscopic approach which is only valid over length scales larger than the ion gyroradius and at timescales longer than the ion gyroperiod.
Frozen-in Flux

The generalised Ohm’s law is given by [Bittencourt, 2004]

\[ \mathbf{E} + \mathbf{v} \times \mathbf{B} = \frac{\mathbf{J}}{\sigma_0} + \frac{\mathbf{J} \times \mathbf{B}}{n_e e} + \frac{m_e}{n_e e^2} \frac{\partial \mathbf{J}}{\partial t} - \nabla \cdot \mathbf{P}_e \]  

(1.31)

\( \sigma_0 \) - electrical conductivity \hspace{1cm} \( \mathbf{P}_e \) - electron pressure

For many space plasmas, most of the terms disappear:

- Hall effect negligible \hspace{1cm} \therefore \frac{\mathbf{J} \times \mathbf{B}}{n_e e} = 0 \hspace{1cm} (1.32)
- Steady state \hspace{1cm} \therefore \frac{\partial \mathbf{J}}{\partial t} = 0 \hspace{1cm} (1.33)
- Electron pressure negligible \hspace{1cm} \therefore \frac{\nabla \cdot \mathbf{P}_e}{n_e e} = 0 \hspace{1cm} (1.34)

Therefore

\[ \mathbf{J} = \sigma_0 (\mathbf{E} + \mathbf{v} \times \mathbf{B}) \]  

(1.35)

If the plasma is collisionless, then \( \sigma_0 \) becomes infinite and Equation 1.35 can only be satisfied if

\[ (\mathbf{E} + \mathbf{v} \times \mathbf{B}) = 0 \]  

(1.36)

This describes what is known as Alfvén’s frozen-in theorem, where magnetic field lines are carried with the plasma or ‘frozen into’ the plasma fluid [Kivelson, 1995].
1.2 Ionisation Processes

Photoionisation

Photoionisation is the process whereby an atom or molecule of any species is ionised through interaction with an incident photon \[McNaught and Wilkinson, 1997\]. In the interaction, an electron (called a photoelectron) is ejected from the molecule. The reaction may be written as

\[
M + h\nu \rightarrow M^+ + e^- \quad (1.37)
\]

\(M\) - molecule species \(\nu\) - photon frequency \(h\) - Planck’s constant

The energy of the ejected photoelectron is known as the excess energy and is given by

\[
\text{Excess Energy} \quad E_e = h\nu - \phi \quad (1.38)
\]

Where \(\phi\) is the threshold energy (or ionisation energy), the minimum energy required to ionise the molecule. Photons with less than this energy may be absorbed or scattered by the molecule, but they cannot photoionise it.

Not every photon which encounters a molecule will interact with and ionise it. The photoionisation cross section, \(\sigma(\lambda)\) represents the probability of an electron being ejected from the molecule by an incoming photon. The photoionisation cross section varies between species and is usually calculated theoretically, being dependant on the quantum structure of the molecule.

Photoionisation is a key process in the context of space plasma and planetary physics. It is one of two ionisation processes which supports planetary ionospheres throughout the solar system (the other being impact ionisation from solar particles and galactic cosmic rays) \[Luhmann, 1995; Russell et al., 2016\]. It also contributes to the production of plasma from magnetospheric neutrals, especially those found in the neutral rich magnetospheres of Saturn and Jupiter. In addition to these large scale processes, photoionisation directly impacts the spacecraft used to measure space plasma in situ. Photoemission from the surface of a spacecraft contributes significantly to the electro-
static potential of the spacecraft and affects the measurement of charged particles (see Section 2.5).

Electron Impact Ionisation

Another common form of plasma production is ionisation of a neutral atom or molecule by the impact of an energetic electron, known as Electron impact ionisation. The reaction may be written as

\[ M + e^- \rightarrow M^+ + 2e^- \]  \hspace{1cm} (1.39)

Impact ionisation is an important process in producing plasma in the ionosphere, especially at high latitudes where high energy electrons following magnetic field lines collide with the neutral atmosphere Baumjohann and Treumann [1996]; Russell et al. [2016]. It is also the main process responsible for the production of plasma from Io’s sulphur emissions in Jupiter’s magnetosphere [Russell and Walker, 1995].
1.3 Plasma Structures in the Solar System

1.3.1 The Heliosphere

A stream of plasma emanates from the Sun in all directions, carrying the Sun’s magnetic field (known as the interplanetary magnetic field (IMF)) with them. These particles form what is known as the solar wind which expands through the solar system at speeds between 200–1000 km s\(^{-1}\) and consists primarily of ionised hydrogen and a small part ionised helium and heavier elements [Hundhausen, 1995]. The region of space which is dominated by the solar wind is known as the heliosphere.

The Sun’s magnetic field is frozen into the expanding solar wind and remains connected to the Sun’s surface. The rotation of the Sun results in a structure known as the Parker spiral [Parker, 1958] and is illustrated in Figure 1.8.

Figure 1.8: Schematic representation of the Parker spiral structure of the interplanetary magnetic field in the ecliptic plane. Figure from Bittencourt [2004].
1.3.2 Planetary Magnetospheres

Planetary bodies with internal magnetic dynamos and therefore their own magnetic fields are surrounded by a region known as the magnetosphere [Walker and Russell, 1995]. It is created by the interaction between the planetary magnetic field and the solar wind. Within this region, the motion of plasma is dominated by interaction with the body’s magnetic field.

Magnetospheres can generally be separated out into different regions. If the incoming solar wind is super-Alfvenic, a bow shock is formed upstream. Behind this is the uppermost region of the magnetosphere known as the magnetopause, which forms the boundary between the planetary field and plasma, and the solar wind. Downstream, the planet’s magnetic field is stretched into what is known as the magnetotail. These regions are shown schematically for Earth’s magnetosphere in Figure 1.9 [Hughes, 1995].

![Diagram of Earth's Magnetosphere](image)

**Figure 1.9:** Schematic configuration of Earth’s magnetosphere in the noon–midnight plane. Distances are indicated in Earth radii. Figure from Bittencourt [2004].

Bulk plasma flow in planetary magnetospheres can be driven internally or externally. The magnetospheres of Earth and Mercury are primarily driven externally by the solar wind whereas internal processes are dominant in Jupiter’s magnetosphere. Saturn’s
magnetosphere exhibits characteristics of both internally and externally driven processes. Until they are studied with long term in situ spacecraft, plasma flow dynamics in the magnetospheres of Uranus and Neptune will remain largely mysterious [Krupp et al., 2010].

**Dungey Cycle**

The driving of a magnetosphere by the solar wind is described by a process known as the *Dungey Cycle* [Dungey, 1961]. The process occurs when a component of the interplanetary magnetic field lines are antiparallel to those of the planetary magnetosphere. A merging between field lines via magnetic reconnection together with the rotation of the planet drives the plasma flow as illustrated in Figure 1.10. Reconnection between the planetary and interplanetary field allows for the entry of solar wind plasma. Precipitation of this solar wind plasma into the atmosphere is responsible for the aurora.

![Flow of plasma within Earth's magnetosphere (convection) driven by magnetic reconnection between the IMF and planetary magnetic field lines. Figure from Hughes [1995].](image-url)

**Figure 1.10:** Flow of plasma within Earth’s magnetosphere (convection) driven by magnetic reconnection between the IMF and planetary magnetic field lines. Figure from Hughes [1995].
Vasyliūnas Cycle

The driving of a magnetosphere by an internal plasma source is described by a process known as the Vasyliūnas Cycle [Vasyliūnas, 1983]. In the case of Jupiter, sulphur emission by Io (which is subsequently ionised) adds a significant amount of mass to the existing corotating flux tubes, stretching them outwards. At Saturn, the internal plasma is generated by ionisation of neutral material emitted by Enceladus [Dougherty et al., 2006]. While the dayside magnetopause forms a boundary to expansion, the plasma can expand into the nightside magnetotail. Eventually the field lines become stretched so thin that they reconnect allowing a self-contained plasmoid to break away down the tail [Gombosi et al., 2009]. The process is shown schematically in Figure 1.11.

![Figure 1.11: Schematic representation of plasma flow in the equatorial plane (left panel) and of the associated magnetic field and plasma flow in a sequence of meridional cuts (right panel). Figure from Gombosi et al. [2009].](image-url)
1.4 The Saturn System

Saturn orbits the sun at an average of 1.4 billion km (roughly 9.5 AU) and is the 6th planet from the sun with a year lasting almost 30 times longer than Earth’s. Saturn is the second largest planet in the solar system after Jupiter with an equatorial radius of 60268 km ($1 R_S$) and a mass of $5.68 \times 10^{26}$ kg. Similar to the other giant planets, Saturn is thought to have a rocky core surrounded by fluid metallic-hydrogen layer [Hubbard et al., 2009] with an atmosphere mostly composed of hydrogen, helium and methane [Fouchet et al., 2009]. Saturn is perhaps most well known for its ring system which are by far the most extensive in the Solar System. Saturn takes 10.5 h to rotate [Read et al., 2009], slightly slower than Jupiter and much faster than the Earth.

Saturn has over 60 moons, 8 of which contain all but a very small fraction of the total orbital mass. Mimas, Tethys, Enceladus and Dione orbit within the E ring ($< 6.5 R_S$). They are known as the icy satellites, are relatively small and composed mostly of water ice. Rhea, Titan, Hyperion and Iapetus are known as the large outer moons and all orbit beyond the E ring (see Figure 1.12 for an artistic impression of the Saturn system out to the orbit of Rhea). Titan is Saturn’s largest moon and the second largest in the solar system after Jupiter’s moon Ganymede and is the only moon in the solar system known to have a dense atmosphere.

| Table 1.1: A selection of Saturn’s physical parameters. From Gombosi et al. [2009]. |
|---------------------------------|-----------|
| Heliocentric distance (AU)      | 9.5       |
| Average IMF magnitude (nT)      | 0.5       |
| Equatorial radius (km)          | 60268     |
| Dipole tilt                     | $<1^\circ$|
| Equatorial magnetic field ($\mu$T) | 20        |
| Equatorial rotation period (hours) | 10.54    |
Figure 1.12: Artistic impression of the Saturn system, showing the rings and the moons of the inner magnetosphere. Image credit: NASA/JPL.
1.4.1 The Magnetosphere

Saturn has the third largest magnetosphere in the Solar System after the Sun and Jupiter. While Earth’s magnetosphere is dominated by solar wind interactions and Jupiter’s is dominated by internal processes, Saturn falls somewhere between the two. It is a fast rotator with an internal plasma source like Jupiter, but a surface magnetic field strength closer to Earth’s, making Saturn’s magnetosphere somewhat unique.

Saturn has a dipole-like intrinsic magnetic field with a dipole axis closely aligned with the rotational axis. The magnetic equator is offset northwards of the rotational equator by $0.0466 R_S$ [Dougherty et al., 2018].
The Rings and Radiation Belts

At the ring system (within $3R_S$), the magnetic field is strongly dipolar and the rings themselves strongly absorb any energetic particles, leaving the region relatively devoid of plasma.

Like the Earth and Jupiter, Saturn has radiation belts which contain trapped energetic charged particles. Although its radiation belts are somewhat weaker than Jupiter’s, this is partly explained by absorption by the icy moons and the rings [André et al., 2008]. The main part of the radiation belt extends from the A ring to the orbit of Enceladus ($2.3-4R_S$) and Cassini discovered an additional radiation belt inside the D ring [Krimigis et al., 2005]. The particles trapped in these radiation belts range from hundreds of keV to tens of MeV and are found mostly inside $6R_S$ [Gombosi et al., 2009] (Figure 1.14).

![Figure 1.14: Spectrograms of energy vs L shell measured by MIMI/LEMMS during Saturn orbital insertion in July 2004. Top) energetic Ion intensities. Bottom) energetic electron intensities. Figure from Gombosi et al. [2009].](image)
1.4. THE SATURN SYSTEM

Inner Magnetosphere

Saturn’s inner magnetosphere extends between \( \approx 3–8 \, R_S \) and is home to the icy satellites: Mimas, Tethys, Enceladus and Dione. The region contains the main sources of cold plasma, neutrals (Section 1.4.2) and dust in the magnetosphere. The neutrals in the inner magnetosphere dominate as the density exceeds that of the local plasma by at least an order of magnitude and is chemically coupled to the ion plasma \cite{Jurac and Richardson, 2007}. This cold plasma is supplied by: photoionisation, charge exchange and electron impact ionisation, and is mostly confined to the equatorial plane leading to a corotating cold plasma torus \cite{André et al., 2008}.

The neutral composition of the inner magnetosphere is dominated by water group molecules. Jurac and Richardson \cite{2007} produced a model of how the neutral density and composition interacts with the rings in the innermost region (shown in Figure 1.15). The inner magnetosphere is clearly dominated by H\(_2\)O and its neutral dissociation products.

Middle Magnetosphere

The middle magnetosphere can be considered to be the region between \( \approx 8–15 \, R_S \). Aside from when transient radiation belts are present \cite{Roussos et al., 2008}, the middle magnetosphere has significantly less intense radiation belt particles than the inner magnetosphere. As the radial distance from Enceladus increases, neutral particle density reduces considerably (\(< 5\% \) equatorial peak density at \( 8 \, R_S \)). In this region the magnetic field begins to depart from the largely dipolar configuration observed in the inner magnetosphere \cite{Arridge et al., 2011}.

Outer Magnetosphere

The outer magnetosphere (outside \( \approx 15 \, R_S \)) features a much more variable magnetic field and plasma content \cite{Arridge et al., 2011}. The magnetopause standoff distance has been found to follow a bimodal distribution with peaks at \( 22 \, R_S \) and \( 27 \, R_S \) (close to the orbit of Titan) \cite{Achilleos et al., 2008}. 
Figure 1.15: Neutral density profiles in the region near the main rings for OH, O, H$_2$O and H. Since the neutrals are lost via collisions with the main rings, the densities drop sharply near the outer edge of the main rings ($2-2.5 R_S$). The largest radial gradient is seen for the H$_2$O molecules which are the slowest, and thus, most constrained to the equatorial plane. These water molecules are preferentially absorbed by the outer edge of the main rings. Figure from Jurac and Richardson [2007].
1.4.2 Enceladus

Enceladus was discovered by William Herschel in 1789 and is Saturn’s sixth largest moon with a radius of 252 km. It orbits in a 2:1 resonance with Dione at \( \approx 23,800 \text{ km} \) which is \( \approx 3.95 R_S \), taking 33 hours to complete one orbit. It has a relatively low density of \( 1.61 \text{ g cm}^{-3} \) and has a water/ice silicate core with a high albedo surface of water ice (Figure 1.16).

There is also mounting evidence that Enceladus has a subsurface ocean between the silicate core and icy surface. Iess et al. [2014] inferred the presence of an ocean beneath the south pole in order to explain variations in the gravitational field. The gravitational field was measured by continuously tracking the spacecraft during three flybys with ground based antennas and measuring the Doppler shifting caused by slight variations in Cassini’s velocity as it passes through the moon’s gravitational field.

Figure 1.16: Mosaic image of the south pole of Enceladus, captured by Cassini on 14th July 2005. Image credit: NASA/JPL, image ID: 220138.
**Enceladus’ Plumes**

Before Cassini arrived at Saturn, there had been some speculation that Enceladus may be active. Unlike the other icy moons of Saturn, Enceladus’ surface is relatively free of craters especially in the southern hemisphere. This implied that Enceladus is, or has been active in the recent past. The moon also orbits at the same distance as Saturn’s tenuous outer E-ring which suggested that Enceladus may be contributing material to the ring [Haff et al., 1983].

Observations from the first few Cassini flybys of Enceladus revealed that gas and ice is actively venting from a series of ridges and troughs (dubbed “tiger stripes”) at the south pole [Dougherty et al., 2006; Porco et al., 2006]. These jets are primarily comprised of water vapour and ice grains [Waite et al., 2006] and forms an extended plume which extends over 4000 km from the surface (Figure 1.17). The plumes eject \( \approx 200 \text{ kg s}^{-1} \) of neutral material, forming the main source of the neutral torus which immerses the inner magnetosphere in an extended cloud of neutral gas [Esposito et al., 2005].

**Figure 1.17:** Image of Enceladus’ south pole captured in November 2005. The image has been enhanced to show the extent of the faint plume. Image credit: Cassini Imaging Team, NASA/JPL/SSI.
1.4. THE SATURN SYSTEM

Enceladus’ Magnetospheric Interactions

At Enceladus’ orbit in Saturn’s inner magnetosphere the plasma is corotating almost rigidly with the planet and so the cold plasma streams past Enceladus causing a cold plasma wake in front of the moon. However more energetic charged particles ($\gtrsim 1 \text{ MeV}$) are significantly affected by gradient and curvature drifts with positive ions drifting with the corotation flow and electrons against it. Electrons $\gtrsim 1 \text{ MeV}$ drift against the corotation flow quickly enough such that their motion relative to Enceladus is in the opposite direction to the corotation flow [Thomsen and van Allen, 1980]. There is also an energetic particle shadow to the north and south of the moon due to the north-south bounce motion of MeV particles trapped in the radiation belts (Figure 1.18).

This shielding from high energy particles results in a significant decrease in MeV proton and electron fluxes close to the orbits of Enceladus and the other icy moons [Paranicas et al., 2005; Roussos et al., 2005]. This depletion is known as a satellite absorption microsignature and has allowed the observation of a number of features at Enceladus which may otherwise been hidden. These observations include negative water cluster ions [Coates et al., 2010], charged dust nanograins [Jones et al., 2009; Hill et al., 2012] and photoelectrons [Coates et al., 2013; Taylor et al., 2018].

Figure 1.18: Enceladus removes high energy charged particles from the magnetosphere through several processes: (a) Collisions with the surface, (b) scattering with E-Ring dust particles, (c) scattering with neutral gas from the plume. Figure from Jones et al. [2006].
1.5 Photoionisation in Space Plasma Environments

Photoionisation (Section 1.2) is the main process responsible for supporting sunlit ionospheres across the solar system. In addition to this, photoelectrons have also been observed in the magnetospheres of several planets. The process can contribute significantly to plasma generation in region where the density of neutrals is high.

Photoelectrons have been observed by spacecraft at Earth [Coates et al., 1985], Venus [Coates et al., 2008], Mars [Frahm et al., 2006] and Saturn [Coates et al., 2005, 2007a; Wellbrock et al., 2012; Schippers et al., 2009; Coates et al., 2013]. A detailed comparison of photoelectrons at Earth, Mars, Venus and Titan was presented by Coates et al. [2011].

1.5.1 Photoionisation at Saturn

Photoelectrons are commonly observed at Saturn in regions of high neutral density. The first regions encountered by Cassini which fits this description were the rings during orbital insertion. Photoelectron signatures were observed in the proximity of Saturn’s A and B rings, thought to be produced from UV ionisation of ring atmosphere particles [Coates et al., 2005]. These photoelectrons exhibit a peaked structure in the 20–25 eV energy range typical of those produced from water group neutrals.

Schippers et al. [2009] presented observations of photoelectron signatures in the inner magnetosphere. In addition to the typically observed ≈20 eV peak, observations included the first observations of a secondary peak at ≈42 eV peak, also associated with photoionisation (Figure 1.19). These photoelectrons are produced by photoionisation of the Enceladus neutral torus in Saturn’s inner magnetosphere and as such, are observed throughout the region (Figure 1.20).
Figure 1.19: (a) Differential number flux spectrum from the combination of CAPS/ELS and MIMI/LEMMS observations obtained by the Cassini spacecraft at 4.4 Rs at 1900 UT on day 104 of 2005. The CAPS/ELS raw data are displayed as a red dash-dotted line, the CAPS/ELS data are displayed with background subtracted as a red solid line, and the MIMI/LEMMS data are displayed in green. (b) The same as (a) with overlaid thermal and suprathermal kappa models. (c) Residuals of differential number flux after the contributions from the thermal and suprathermal populations have been removed. Gaussian distributions are fitted to the two observed narrow peaks (in the 10–100 eV energy range). Figure from Schippers et al. [2009].
Figure 1.20: Identification of narrow peaks in the Krono-centric Saturn Equatorial coordinate system (KSE). (a) Location of narrow peaks in the equatorial plane (in red on the Cassini trajectory). (b) Location of narrow peaks in the meridian plane (in red). Dipolar magnetic field lines are overlaid in blue. The position of the inner icy satellite orbits is overlaid in green. Figure from Schippers et al. [2009].

Coates et al. [2013] presented observations of photoelectron signatures specifically associated with the plumes of Enceladus (Figure 1.21). The reduction in penetrating radiation due to the shielding by Enceladus allows the observation of low energy electrons in the region close to the moon. This study presented the first observations of freshly produced photoelectrons from the plume of Enceladus itself, rather than from the neutral torus.
1.6 Thesis Outline

This chapter has introduced the basic concepts of space plasma physics and introduced the reader to the Saturn system forming a basis for the original research in later chapters. Chapter 2 contains an introduction to the instrumentation used throughout this thesis.

This thesis is structured around three research projects all taking advantage of Cassini data taken in Saturn’s inner magnetosphere. Each study attempts to address some aspect of these three themes:

- Photoelectron dynamics
- Magnetospheric eclipsing
- Spacecraft shadowing and charging effects
Chapter 3 focusses on the analysis of electron spectra observations made by Cassini at Enceladus. The study uses modelling and background subtraction techniques previously used in the inner magnetosphere to reveal and explain new complex low energy electron spectra in the plume.

In Chapter 4, observations of photoelectron peaks while the spacecraft is fully eclipsed by Saturn are presented and analysed. The complex geometry of Saturn’s shadow projected through the inner magnetosphere is modelled and considered in an effort to determine a possible source and transport method for the observed photoelectrons.

Chapter 5 continues to explore the shadow of Saturn and its moons, this time focussing on the effect of eclipsing on the spacecraft itself and the local plasma. A series of case studies are presented and the spacecraft potential changes are estimated as the shadow boundary is crossed.

Chapter 6 summarises the research results in previous chapters and discusses the conclusions in context of the three main themes. Some of the implications for these studies and possible future work are also addressed.
Chapter 2

Instrumentation

Photographs from the launch of the Titan IVB/Centaur carrying the Cassini-Huygens spacecraft on 15th October 1997. Image credit: NASA.

2.1 Cassini-Huygens

The Cassini-Huygens mission was a joint flagship class NASA-ESA-ASI endeavour, the fourth spacecraft to visit Saturn and the first to enter orbit around the planet. The mission followed on from flybys in 1979 by Pioneer 11 and in 1980 and 1981 by both
Voyager spacecraft. The spacecraft consisted of two parts, the orbiter Cassini (NASA-ASI) and a Titan lander Huygens (ESA). Cassini was named after the Italian-French astronomer Giovanni Domenico Cassini who discovered Iapetus, Rhea, Tethys and Dione in the latter half of the 17th century. The Huygens probe was aptly named after Dutch astronomer Christiaan Huygens, the discoverer of Saturn’s largest moon Titan in 1655.

The spacecraft launched on the 15th October 1997 aboard a Titan IVB/Centaur from Cape Canaveral. Cassini-Huygens entered Saturn orbit on 1st July 2004 after an interplanetary journey taking 7 years and involving an Earth, two Venus and a Jupiter gravity assist flybys (Figure 2.1). The Huygens probe was released from the orbiter on 25th December 2004 and landed at Titan on 14th January 2005. It was the first probe landed on a body in the outer solar system and the first to land on a moon other than our own.

Figure 2.1: Cassini-Huygens mission trajectory from Earth to Saturn including an Earth, two Venus and a Jupiter gravitational assist manoeuvres. Figure credit: MPS.
2.1. CASSINI-HUYGENS

Cassini had an extremely successful four year *Prime Mission* (completed in June 2008) and was extended numerous times. Following was the two year *Cassini Equinox Mission* (completed September 2010) and seven year *Cassini Solstice Mission* (completed May 2017). The 4 month *Grand Finalé Mission* ended on the 15th September 2017 with the planned destruction of the spacecraft in Saturn’s atmosphere after a series of 22 ‘proximal orbits’ with periapsis inside the inner edge of the rings (Figure 2.2).

![Figure 2.2](image)

*Figure 2.2:* Illustration showing Cassini’s orbits during the final stages of the mission before its eventual destruction. Figure credit: JPL.
2.1.1 Instruments

The Cassini spacecraft (Figure 2.3) carried 12 instruments on board (Table 2.1) in order to study the planet, the rings, the magnetosphere and its moons, Titan in particular.

![Diagram of the Cassini Spacecraft](image)

Figure 2.3: Diagram of the Cassini Spacecraft showing the locations of many of the instruments and components. Figure from Burton et al. [2001].

<table>
<thead>
<tr>
<th>Cassini Instruments</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAPS</td>
</tr>
<tr>
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</tr>
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<td>CIRS</td>
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<td>INMS</td>
</tr>
<tr>
<td>ISS</td>
</tr>
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<td>MIMI</td>
</tr>
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</tr>
<tr>
<td>UVIS</td>
</tr>
<tr>
<td>VIMS</td>
</tr>
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</table>
2.2 The Cassini Plasma Spectrometer (CAPS)

The Cassini Plasma Spectrometer (CAPS) contained a suite of three sensors: the Electron Spectrometer (ELS), the Ion Beam Spectrometer (IBS) and the Ion Mass Spectrometer (IMS) (Figure 2.4) [Young et al., 2004]. CAPS had an extremely successful 14 year long operational lifetime including 7 years at Saturn before being temporarily switched off between June 2011 and March 2012 due to anomalous short circuits on the spacecraft [NESC, 2012]. It operated again until June 2012 before being unfortunately shut down for the remainder of the mission. It was mounted on a motorised actuator which sits on the fields-and-particles pallet (Figure 2.5). The actuator rotated through a maximum of $\pm 104^\circ$ at a speed of 1° per second about the spacecraft’s Z-axis (Figure 2.3).

![Cross sectional diagram of the CAPS instrument showing the Electron Spectrometer (ELS), the Ion Beam Spectrometer (IBS) and the Ion Mass Spectrometer (IMS). Figure from Young et al. [2004].](image-url)
Due to its placing on the fields-and-particles pallet, the CAPS field-of-view (FOV) was not entirely clear and parts of the sky are obscured by other parts of the spacecraft (Figure 2.6).

![Figure 2.5: Location and orientation of instruments mounted on the fields-and-particle pallet. Figure from Young et al. [2004].](image)

**Figure 2.5:** Location and orientation of instruments mounted on the fields-and-particle pallet. Figure from Young et al. [2004].

![Figure 2.6: All-sky projection of IMS field-of-view, obscuration is caused by other parts of the spacecraft. ELS and IBS are mounted nearby and so have similar fields-of-view. The obstacles include: parts of the spacecraft thrusters, the mount for Huygens, the High Gain Antenna (HGA), the fields-and-particle pallet structure (FPP), the MIMI-LEMMS instrument and part of the shield for the Radioisotope Thermoelectric Generators (RTG). Figure from Young et al. [2004].](image)

**Figure 2.6:** All-sky projection of IMS field-of-view, obscuration is caused by other parts of the spacecraft. ELS and IBS are mounted nearby and so have similar fields-of-view. The obstacles include: parts of the spacecraft thrusters, the mount for Huygens, the High Gain Antenna (HGA), the fields-and-particle pallet structure (FPP), the MIMI-LEMMS instrument and part of the shield for the Radioisotope Thermoelectric Generators (RTG). Figure from Young et al. [2004].
2.2. THE CASSINI PLASMA SPECTROMETER (CAPS)

2.2.1 Electron Spectrometer (ELS)

The CAPS electron spectrometer (CAPS-ELS) [Young et al., 2004; Linder et al., 1998] was a hemispherical top-hat electrostatic analyser. Electrons enter the instrument, pass between concentric hemispherical electrostatic analyser plates before hitting an annular microchannel plate (MCP) detector (shown in Figure 2.4). It measures electrons in an energy range of 0.6–28000 eV q⁻¹ with an energy resolution of 16.7% (Table 2.2) and a sweep time of 2 s. The total angular coverage is 160° by 5° split equally between 8 anodes which have angular coverage of 20° by 5° orientated about the spacecraft’s X-axis. The field-of-view is further increased by the rotation of the actuator CAPS is mounted on.

Table 2.2: CAPS-ELS bin numbers and measured energy values in eV [Lewis et al., 2010]. The 64th flyback bin is omitted.

<table>
<thead>
<tr>
<th>Bin</th>
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<th>Bin</th>
<th>Energy (eV/q)</th>
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</table>
2.2.1.1 Geometric Factor

In order to use the instrument data effectively, the raw electron counts measured by the instrument must be converted into scientifically useful units. To do this, a geometric factor $G$ is calculated using Equation 2.1.

\[
G = dA \cdot dA_Z \cdot dL \cdot dE
\]  
(2.1)

- $dA$ - effective area of the sensor (m$^2$)
- $dA_Z$ - effective azimuthal angular width of the sensor (radians)
- $dL$ - width of the energy aperture
- $dE$ - width of the energy aperture, passband $\Delta E/E$ (eV eV$^{-1}$)

Therefore, the units of $G$ are m$^2$ sr eV eV$^{-1}$ [Linder et al., 1998; Young et al., 2004; Rymer, 2004; Lewis et al., 2008].

As well as taking into account the dimensions of the instrument, the efficiency of the MCPs are included in the calibration. As the MCPs have degraded during the mission, the efficiency has decreased. This reduction in efficiency is accounted by cross-calibrating with other instruments in flight [Lewis et al., 2010].

2.2.2 Ion Mass Spectrometer (IMS)

The CAPS ion mass spectrometer was a toroidal electrostatic analyser which measured positive ions in an energy range of 1–50 280 eV q$^{-1}$ with an energy resolution of 17% [Young et al., 2004]. The total angular coverage is 160° by 8° split equally between 8 anodes. IMS was also capable of making time-of-flight (TOF) measurements using a linear electric field, measuring particle velocity. Combining these properties allows the measurement of the particle mass/charge and therefore produced positive ion compositions.
2.3 Radio and Plasma Wave Science (RPWS)

The Cassini radio and plasma wave science instruments (RPWS) consisted of three electric field antennas, three search coil magnetic antennas and a Langmuir probe (LP) [Gurnett et al., 2004].

2.3.1 Langmuir Probe (LP)

Like many spacecraft before it, Cassini was equipped with a Langmuir probe instrument. Cassini’s was a spherical metallic sensor mounted on a 1.5 m boom which was used to measure electron density and temperature. Langmuir probes operate by applying a voltage to the spherical sensor which causes generates a current in the ambient plasma. This current can be measured and used to measure plasma characteristics and to determine the spacecraft potential. The langmuir probe spacecraft potential technique has some limitations when the $\lambda_D$ is close to or larger than the boom length or when the boom is in the spacecraft wake/sheath. In this thesis, spacecraft potential measurements from RPWS are compared to those made using CAPS data in Chapter 3.

2.4 Plasma Instrument Scientific Units

The CAPS instrument measured incident charged particles using MCPs. The impact of single particles are multiplied via secondary emission finally producing a single ‘count’ reading. The counts are summed over an accumulation time to produce the raw measurement, counts per accumulation, $C_{ac}$. For ELS, the accumulation time is 23 ms ($\frac{2s}{64 \text{ bins}} \times 0.75s$ (voltage settling time) = 23 ms). In order to analyse the data it is usual to convert this instrument-specific measurement into scientific units to compare with other data sets and to measure the plasma parameters [Rymer, 2004; Lewis et al., 2008; Regoli, 2016]. These units can be calculated sequentially.

Counts per Second

The first derived unit is counts per second $C_S$, which is simply the counts per accumulation divided by the accumulation time of the instrument $dt$ (Equation 2.2).

$$C_S = \frac{C_{ac}}{dt}$$ (2.2)
**Differential Energy Flux (DEF)**

The first calibrated scientifically useful unit used is the *differential energy flux*, $f_{\text{DEF}}$ (units of $\text{m}^{-2} \text{sr}^{-1} \text{s}^{-1}$). It is calculated using the instrument geometric factor $G$ to account for the dimensions of the instrument and MCP efficiencies (Equation 2.3).

\[
f_{\text{DEF}} = \frac{C_S}{G}\]  

(2.3)

**Differential Number Flux (DNF)**

The second scientific unit used is the *differential number flux* (units of $\text{m}^{-2} \text{sr}^{-1} \text{s}^{-1} \text{J}^{-1}$) which is calculated by dividing by the energy of the charged particle being measured (Equation 2.4).

\[
f_{\text{DNF}} = \frac{f_{\text{DEF}}}{E}\]  

(2.4)

**Phase Space Density (PSD)**

Finally, the *phase space density*, $f_{\text{PSD}}(x,v,t)$, (units of $\text{m}^6 \text{s}^3$) is calculated by dividing by $v^4$ (where $v = \sqrt{\frac{2E}{m}}$). *N.B.* The missing factor 2 is accounted for within $G$ (Equation 2.5).

\[
f_{\text{PSD}} = \frac{f_{\text{DEF}}}{v^4} = \frac{f_{\text{DEF}} \cdot m^2}{2E^2}\]  

(2.5)
2.5 Spacecraft Potential

The surface of a spacecraft travelling through a space plasma is exposed to constant bombardment by incident charged particles Whipple [1981]. Under differing conditions, spacecraft can become both positively or negatively charged, affecting the motion of surrounding charged objects. The build up of charge on a spacecraft can cause problems both operationally and for any instruments attempting to measure charged particles or fields as the spacecraft’s own potential will affect the measurements.

2.5.1 Charging processes

A plasma is an ionised gas usually consisting of positively charged hydrogen nuclei and negative free electrons (see Section 1.1.1). A spacecraft immersed in a plasma is constantly impacted by charged particles from the surrounding plasma, facilitating transfer of charge between the spacecraft and its environment. The most important factors which determines spacecraft potential ($\Phi_{SC}$) are transfer of charge from plasma particles, secondary electron emission and photoemission from the spacecraft surface.

Electron impact

Electrons have significantly less mass than the ions in the plasma and so in a plasma at thermal equilibrium, travel much more quickly ($E = \frac{1}{2}mv^2$). This means the net flux of electrons impacting the spacecraft is much higher than that of ions Garrett and Whittlesey [2012]. At low energies (<10 eV), impacting electrons will almost always ‘stick’ to the surface of the spacecraft, adding their negative charge to the potential of the spacecraft. At higher energies (>10 eV), impacting electrons can cause secondary electron emission from the surface, removing negative charges from the surface and driving the potential more positive.

Ion impact

Relatively low energy ions passing within 0.1 nm can pull electrons from the surface via field emission, becoming neutral in the process. Energetic ions (>10 keV) can cause secondary electron emission by impacting in the same way as energetic electrons.
Photoemission

When in sunlight, incident photons result in the photoemission of electrons from the surface of the spacecraft (see Section 1.2). This process drives a constant reduction in negative charges, driving the spacecraft potential more positive in sunlight.

These processes are each illustrated in Figure 2.7. The rate at which these competing processes proceed is dependent both on the characteristics of the surrounding plasma and the body itself. Many of the processes are dependent on the charge already held by the spacecraft. For example, if a spacecraft is sufficiently positively charged, electrons produced by photoemission or impact may be attracted back to the spacecraft and not escape. A negatively charged spacecraft will attract ions and repel electrons, increasing and decreasing the flux of those particles to the spacecraft respectively.

The final potential of the spacecraft is the result of a balance between all these charge transfer mechanisms [Whipple, 1981; Johnstone et al., 1997]. Generally the equilibrium potential of a spacecraft will not be neutral. The current balance can be expressed for a uniformly conducting spacecraft as [Garrett, 1981; Garrett and Whittlesey, 2012]

\[
I_{\text{total}} = I_E(V) - [I_I(V) + I_{\text{photo}}(V) + I_{\text{secondary}}(V)]
\]

\(V\) - spacecraft potential relative to the local plasma

\(I_{\text{total}}\) - total current to the spacecraft

\(I_E\) - incident electron current to the spacecraft

\(I_I\) - incident ion current to the spacecraft

\(I_{\text{photo}}\) - photoelectron current

\(I_{\text{secondary}}\) - additional secondary electron currents (i.e. produced by spacecraft operations)
2.5. SPACECRAFT POTENTIAL

2.5.2 Plasma parameters

A spacecraft may undergo changes in potential as its environment changes. The rate of photoemission depends only on the flux of incident photons and aside from eclipsing events, remains virtually constant at all times. Plasma density however varies widely in space plasmas and spacecraft can regularly travel between regions of high and low density over an orbit. Due to the imbalance in electron and ion fluxes to the spacecraft, the negative current increases with plasma density. In Cassini data it is observed that spacecraft potential is negative throughout Saturn’s inner magnetosphere. The threshold where the balance of potential becomes positive occurs at around $12 R_S$ [Livi et al., 2014].

All charged particle and field measurements (especially at low energies $< 100 \text{ eV}$) rely on an accurate estimation of the spacecraft potential at the time of measurement. This is especially important when the measurement energy is comparable to or less than the spacecraft potential ($\Phi_{SC} \ll E_{\text{measurement}}$). Spacecraft potential is an important compo-
Liouville’s Theorem

Liouville’s theorem states that in the absence of collisions, phase space density is constant along a particle trajectory, i.e. $\frac{df_{psd}}{dt} = 0$ [Russell et al., 2016]. This means the phase space density of an incoming charged particle distribution accelerated/decelerated by the potential of the spacecraft (via the Lorentz force) must remain constant. This can be used to analyse the effect of spacecraft potential on the observations made by a charged particle instrument. Total phase space density is conserved and so when phase space density is plotted against energy, only an energy shift is observed. Figure 2.8 illustrates the effect of spacecraft potential on the measurements of electron and ion distributions by a spacecraft.
Figure 2.8: Diagram showing how electron (left panels) and ion (right panels) distributions as measured by spacecraft instruments are affected by the potential of the spacecraft $\phi$. Each panel shows a particle distribution of phase space density vs energy (eV) both on linear scales. The centre panels show a Maxwellian distribution as measured by a neutral spacecraft. The top panels show the same Maxwellian distribution as measured by a positively charged spacecraft (red), compared with the distribution measured by a neutral spacecraft (dashed black). Notable in the electron panel are spacecraft photoelectrons $e_{\text{photo}}$ visible at energies below the spacecraft potential cut-off at $\phi$. The bottom panels show the same Maxwellian distribution as measured by a negatively charged spacecraft (blue), compared with the distribution measured by a neutral spacecraft (dashed black).
Chapter 3

Photoelectrons at Enceladus

The plumes of Enceladus backlit by the sun as seen from Cassini. Image credit: NASA/JPL-Caltech/SSI.

One of Cassini’s science objectives was to study the icy moons of Saturn, including Enceladus. After the detection of the plume by the Cassini Magnetometer [Dougherty et al., 2006] and the Imaging Science Subsystem [Porco et al., 2006], Enceladus has been of great interest and is the second most visited moon after Titan. In addition to the extensive data collected by the remote imaging instruments, the plume has been sampled directly by Cassini’s in situ instruments including CAPS.

This chapter presents observations of fine photoelectron structure near Enceladus, including the identification of previously unreported low energy peak structure. Mod-
elling reveals that these photoelectron peaks are likely to originate in the plume dense plume material.

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### 3.1 Introduction

Photoionisation is the physical process where a neutral atom or molecule becomes ionised by the interaction with a photon producing a photoelectron and a positive ion (Section 1.2). The photoelectrons produced in this process have well-defined energies that correspond to the energy difference between the incoming photon and the ionisation potential of the neutral atom or molecule [Huebner et al., 1992]. In our solar system, the Sun provides the extreme ultraviolet (EUV) photons required to produce photoelectrons and they are present wherever neutral atoms and molecules are found. Photoionisation is a key ionospheric process at every body with an atmosphere, and photoelectrons have been measured directly by spacecraft at Earth [Coates et al., 1985], Venus [Coates et al., 2008] and Mars [Frahm et al., 2006]. Since the arrival of Cassini at Saturn, photoelectrons have been observed in the Saturnian ring exosphere [Coates et al., 2005], Titan [Coates et al., 2007a; Wellbrock et al., 2012], throughout the inner magnetosphere [Schippers et al., 2009] and in the plume of Enceladus [Coates et al., 2013; Ozak et al., 2012]. A comparison of photoelectrons at Earth, Mars, Venus and Titan was presented by Coates et al. [2011].

The energy spectra of solar system photoelectrons often exhibit a number of unique features. Pronounced peaks in the 20–30 eV energy range have been observed in many
planetary atmospheres and is associated with the ionisation of neutrals by the strong He-II 30.4 nm solar emission line. The particular electron energy spectrum observed in an atmosphere depends on the neutrals present and the branching ratios for each photoionisation reaction \cite{Mantas and Hanson, 1979}. Another feature is an observed drop off of photoelectron production above \( \approx 60\ \text{eV} \) which is due to a reduction in solar photon intensity at wavelengths below 16nm \cite{Galand et al., 2006; Coates et al., 2011}. Saturn’s inner magnetospheric region extends from the edge of the main rings to \( \approx 6 R_S \) (\( 1 R_S = \) one Saturn radii \( \approx 60268 \) km) \cite{Arridge et al., 2011}. The magnetic field is dominated by the planetary internal field and is strongly dipolar throughout the region. The inner magnetosphere is immersed in an extended cloud of neutral gas. This gas is chemically coupled to the ion plasma and its density exceeds that of the local plasma by at least an order of magnitude \cite{Jurac and Richardson, 2007}. This neutral gas has been measured by Cassini’s Ion and Neutral Mass Spectrometer (INMS) \cite{Perry et al., 2010} and the Ultraviolet Imaging Spectrometer (UVIS) \cite{Esposito et al., 2005} and is composed mainly of \( \text{H}_2\text{O} \) and its dissociation products. Cold plasma is supplied by a number of different processes including: photoionisation, charge exchange and electron impact ionisation. It is mostly confined to the equatorial plane leading to a corotating cold plasma torus \cite{André et al., 2008}. Warm electrons, some of which are produced by photoionisation \cite{Coates et al., 2013}, may provide an important ionisation source in the inner magnetosphere \cite{Fleshman et al., 2012}. Saturn’s radiation belts are most intense in the inner magnetosphere and so in addition to neutrals and cold plasma, the region is populated by trapped energetic (MeV) charged particles \cite{Krupp et al., 2009; Paranicas et al., 2010}.

Enceladus is Saturn’s sixth largest moon with a radius of \( R_{\text{En}}=252 \) km. It orbits well within the inner magnetosphere and radiation belts at \( 3.95 R_S \). Enceladus was identified as the primary source of the neutrals in the inner magnetosphere with the discovery of active venting from the moon’s south pole which resulted from Cassini observations \cite{Dougherty et al., 2006}. Plumes of neutral particles \cite{Waite et al., 2006} and micron-sized icy dust particles \cite{Spahn et al., 2006} have been discovered emanating from “tiger stripe” features on the icy surface at high southern latitudes \cite{Porco et al., 2006}. Significant quantities of these neutral particles become charged and Cassini has
detected plasma [Tokar et al., 2006, 2009] (including water group ion clusters [Coates et al., 2010]) and charged nanograins [Jones et al., 2009; Hill et al., 2012] in the plumes.

In this chapter a further study of the “magnetospheric” and “plume” photoelectrons identified by Schippers et al. [2009] and Coates et al. [2013] is presented. The modelling technique used to identify photoelectron signatures in the magnetosphere (Schippers et al. [2009]) is applied to the dense plume region. This is made possible as a region of the plume is shielded from energetic charged particles by Enceladus itself. The photoelectron signature is separated from the background electron signature and a previously hidden multiple peak structure is identified. This structure is present in both the magnetospheric and plume photoelectron signatures. A post-hoc Wilcoxon Signed-Rank (WSR) [Gibbons and Chakraborti, 2011; Sprent and Smeeton, 2016] non-parametric test of paired comparisons, using a normal approximation method, indicates there are no statistically significant differences between the modelled background distribution and the ELS data. The subtracted ELS energy spectra from the E9 and E19 Enceladus flybys is compared with a model of the plume photoelectron production rate. In addition to the two previously identified photoelectron peaks, a further low energy photoelectron energy structure is identified and the ratios between the two main peaks (C and D) is investigated.

3.2 Flyby Orientations

Cassini performed 23 flybys of Enceladus over the course of its mission making many discoveries, some of which are discussed in Section 1.4.2. CAPS was operational for 17 of them, covering a variety of different trajectory orientation, local times, closest approach distances and instrument pointing angles. This information is summarised in Table 3.1.

Four classifications are used to describe the orientation of each Enceladus encounter: Upstream, North-South, Southern and Northern. Figure 3.1 shows the geometry of a flyby from each of these classifications. These trajectory plots use an Enceladus centred coordinate system: The X coordinate points along Enceladus’ orbital motion,
Figure 3.1: Diagram showing typical geometry of each flyby trajectory classification. The green shaded region shows the nominal location of the co-rotation wake and the blue shaded region shows the region directly south of the disk of Enceladus where the plume is directly encountered.

$Y$ points towards Saturn and $Z$ is aligned with Enceladus’ rotation axis and completes the right-handed set.

The format of these plots is as follows; Panel $a$ shows the view down onto the northern pole of Enceladus, the corotation wake is in $+X$ and Saturn is in the $+Y$ direction. Panel $b$ shows the view in Enceladus’ orbital plane with Saturn in the background. The corotation wake is again in $+X$ and the plume extends in $-Z$, south of the moon. Panel $c$ shows the final projection, the view along the co-rotation wake with Saturn off in $+Y$ and the plume again extending in $-Z$. The arrows on each trajectory line show the direction the spacecraft travelled.
Generally, the classifications are defined as follows:

- **North-South**: Crosses north to south, passing through the plume
- **South**: Passes under south pole, passing through the plume
- **North**: Passes over the north pole
- **Upstream**: Passes upstream of the corotation wake

Figure 3.1 shows a few example flybys from these classifications. E1 was an encounter in which the spacecraft passed upstream of Enceladus, not passing directly north or south of the disk of the moon. E6 was a North-South encounter in which the spacecraft crossed through the corotation wake from the north to the south before passing to the south of the disk. E9 and E19 were Southern encounters during which the spacecraft crossed directly south of the disk.

In this study, data from flybys across each classification was examined and two were selected for further analysis. The selection criteria for choosing flybys suitable for investigating photoelectrons at Enceladus are as follows: The closest approach is within $2 R_{En}$ and the ram angle is large (i.e. the instrument is pointing away from the ram direction so dust and negative ions are not measured [Jones et al., 2009; Coates et al., 2010]). Applying these criteria leaves us with flybys: E1, E2, E6, E9, E12, E13 and E19 (see Table 1 in Coates et al. [2013] for further information on each Enceladus flyby where CAPS data are available). The E9 and E19 flybys are then analysed in further detail by comparing the data to a plume photoelectron model. As well as satisfying the previous conditions, these southern flybys are most suitable for analysing the plume because they pass though it horizontally and the distance to the surface does not vary significantly over the flyby. The other flyby classification which encounters the plume are North-South crossings during which the distance to the surface varies considerably throughout the encounter and as such is a much more complicated situation to analyse.
Table 3.1: Summary of Enceladus flybys where there are CAPS-ELS data.

<table>
<thead>
<tr>
<th>Flyby</th>
<th>Date (DOY)</th>
<th>CA (UT)</th>
<th>CA (LT)</th>
<th>CA (km)</th>
<th>EPS ram angle (deg)</th>
<th>Ram Actuation</th>
<th>Trajectory class</th>
<th>Plume encounter</th>
</tr>
</thead>
<tbody>
<tr>
<td>E0</td>
<td>17/02/05 (048)</td>
<td>03:30:29</td>
<td>22:37:27</td>
<td>1257</td>
<td>87 ± 20</td>
<td></td>
<td>Upstream</td>
<td></td>
</tr>
<tr>
<td>E1</td>
<td>9/03/05 (068)</td>
<td>09:08:01</td>
<td>17:02:19</td>
<td>492</td>
<td>42-50 ± 10</td>
<td></td>
<td>Upstream</td>
<td></td>
</tr>
<tr>
<td>E2</td>
<td>14/07/05 (195)</td>
<td>19:55:22</td>
<td>17:04:16</td>
<td>164</td>
<td>79-78 ± 10</td>
<td></td>
<td>Upstream</td>
<td></td>
</tr>
<tr>
<td>E3</td>
<td>12/03/08 (072)</td>
<td>19:06:12</td>
<td>23:10:58</td>
<td>47</td>
<td>9^{+10}_{-7}</td>
<td>✓</td>
<td>North-South</td>
<td>✓</td>
</tr>
<tr>
<td>E4</td>
<td>11/08/08 (224)</td>
<td>21:06:00</td>
<td>22:41:48</td>
<td>45</td>
<td>158-163^{+5}_{-10}</td>
<td>North-South</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>E5</td>
<td>09/10/08 (283)</td>
<td>19:07:00</td>
<td>22:32:51</td>
<td>19</td>
<td>8^{+10}_{-5}</td>
<td>North-South</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>E6</td>
<td>31/10/08 (305)</td>
<td>17:15:00</td>
<td>22:19:24</td>
<td>191</td>
<td>60-150</td>
<td>✓</td>
<td>North-South</td>
<td>✓</td>
</tr>
<tr>
<td>E7</td>
<td>02/11/09 (306)</td>
<td>07:42:00</td>
<td>10:54:52</td>
<td>91</td>
<td>10 ± 10</td>
<td>South</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>E8</td>
<td>21/11/09 (325)</td>
<td>02:10:00</td>
<td>03:41:23</td>
<td>1594</td>
<td>22-25 ± 10</td>
<td>South</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E9</td>
<td>28/04/10 (118)</td>
<td>00:11:00</td>
<td>09:20:19</td>
<td>91</td>
<td>64 ± 10</td>
<td>South</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>E10</td>
<td>18/05/10 (138)</td>
<td>06:04:00</td>
<td>03:55:40</td>
<td>192</td>
<td>10 ± 10</td>
<td>Upstream</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E11</td>
<td>13/08/10 (225)</td>
<td>22:30:59</td>
<td>03:36:43</td>
<td>2542</td>
<td>80-40 ± 4</td>
<td>South</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E12</td>
<td>30/11/10 (334)</td>
<td>11:53:59</td>
<td>08:49:33</td>
<td>40</td>
<td>72 ± 10</td>
<td>North</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E13</td>
<td>21/12/10 (355)</td>
<td>01:08:26</td>
<td>08:45:16</td>
<td>40</td>
<td>33 ± 10</td>
<td>North</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E17</td>
<td>27/03/12 (087)</td>
<td>18:30:09</td>
<td>00:36:22</td>
<td>65</td>
<td>17-5 ± 10</td>
<td>South</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>E18</td>
<td>14/04/12 (105)</td>
<td>14:01:38</td>
<td>00:35:09</td>
<td>65</td>
<td>18-8 ± 10</td>
<td>South</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>E19</td>
<td>2/05/12 (123)</td>
<td>09:31:29</td>
<td>00:32:40</td>
<td>65</td>
<td>93 ± 10</td>
<td>South</td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>
3.3 Observations

3.3.1 Flyby Survey

Conveniently, Enceladus naturally shields Cassini’s instruments from the penetrating radiation in Saturn’s inner magnetosphere during flybys of the moon (Section 1.4.2). During many of these flybys, the energetic particle shadow forms an obvious signature of reduced counts across all energies in the spectrograms (Figure 3.2). The average intensity of each energy bin across the flyby is also shown in Figure 3.2 and in all cases shows a peak at $\approx 20$ eV.

Figure 3.2: Energy-intensity time averages and energy spectrogram for each flyby showing a clear particle shadow. Time averages are averaged across the time indicated by the black vertical lines in the spectrogram.
In Figure 3.3, a direct comparison is made between the flybys which show good penetrating radiation removal (E0, E4 and E8 are excluded as they show only partial removal). A population of electrons are visible at $\approx 20–30\,\text{eV}$ and are interpreted as photoelectrons produced from the photoionisation of the neutral cloud by the He-II resonance line at 30.4 nm [Cravens et al., 2011]. Also highlighted is a possible peak at $\approx 40–50\,\text{eV}$, apparently consistent with the population (20–50 eV) reported to be detected at 4–5 $R_S$ in Schippers et al. [2009].

![Figure 3.3: Energy-intensity time averages taken across Enceladus flybys showing a primary peak at 20–30 eV and a secondary peak at 40–60 eV. Intensity is measured in differential electron flux. The dashed line represents the level registered by one electron in each energy bin.](image)

### 3.3.2 Flybys E9 and E19

In this chapter we focus on the two best flybys for observing plume photoelectrons: E9 and E19. In Figures 3.4a and 3.4c, an energy-time spectrogram is shown for Enceladus flybys E9 and E19 respectively. A thermal magnetospheric electron population is visible across the spectrogram of both flybys at measured energies below $\approx 8\,\text{eV}$. The high count rate across all energies before and after the flyby is caused by penetrating radiation. This penetrating radiation is primarily caused by energetic electrons (> 800 keV) penetrating the 1.6 nm aluminium thick instrument shielding Rymer et al. [2001]. In the centre of the plots there are significant drops in the count rate, called the ‘energetic particle shadow’. This is caused by penetrating radiation being absorbed by the moon and the plume [Jones et al., 2006]. The energetic particle shadow al-
allows the observation of a number of features during the flyby including the presence of photoelectrons throughout the flyby produced by the ionisation of neutrals both in the Enceladus plume [Coates et al., 2013] and throughout the inner magnetosphere [Schippers et al., 2009]. There are two populations labelled ‘photoelectrons’: Peak C at 16–30 eV and Peak D at 30–60 eV (these will be compared to similarly labelled model peaks later in the chapter).

During the energetic particle shadow of E19 (Figure 3.4a) there are a number of interesting features in the magnetospheric electron population around closest approach. There is a sharp reduction in the magnetospheric electrons (< 8 eV) which is thought to be caused by attachment to ice grains in the plume [Coates et al., 2013]. This feature is very well defined as the grains in the plume form a highly collimated beam (radius ≈ 1 R_{En}) while the neutral gas spreads out much further [Hill et al., 2012; Dong et al., 2015]. Either side of this feature, there appears to be energy shifts in this population thought to be due to sharp spacecraft potential changes [Coates et al., 2013].
3.3. OBSERVATIONS

Figures 3.4b and 3.4d show an energy spectrum at time T in each respective spectrogram. Peaks C and D are the same as labelled in Figures 3.4a and 3.4c, and are interpreted as photoelectrons [Coates et al., 2013; Schippers et al., 2009]. These photoelectrons are a combination of both magnetospheric photoelectrons (generated from neutrals in the magnetosphere) and plume photoelectrons (generated from neutrals in the plume). These plots show the electron spectra close to the plume, where the neutral density is high and there is a sharp increase in the total photoelectron flux due to the local production of plume photoelectrons. The integration times of several sweeps (each sweep is 2s) are short to capture the peak production time while maintaining a good signal-to-noise ratio. The peaks are reminiscent of photoelectron peaks appearing in modelled plume electron fluxes by [Ozak et al., 2012]. Peak C is associated by photoionisation from the strong He-II solar emission line at 30.4 nm. In other environments such as at Titan, the peak is relatively sharp in contrast to Enceladus where the peak is broad and exhibits a complex structure.

In order to further characterise these observed photoelectron peaks, the background magnetospheric electron population must be subtracted. Kappa distributions have been widely used to describe the velocity distributions of space plasmas throughout the solar system [Vasyliūnas, 1968; Collier and Hamilton, 1995; Schippers et al., 2008]. In Saturn’s inner magnetosphere, it has been shown that a double-Kappa distribution can be used to represent the magnetospheric electron population [Schippers et al., 2008]. In the case of ELS data during the Enceladus flybys, it is possible to fit a single Kappa distribution in order to subtract the magnetospheric population. It is not possible to fit a second Kappa distribution due to limited counts at higher energies (> 100 eV).

Figure 3.5 shows the results of applying the Kappa subtraction to the ELS data averaged over 6 and 4 seconds during the energetic particle shadows of E9 and E19. Panels a and c shows the Kappa distribution fit plotted alongside the ELS data. Panels b and d shows the residual flux once the Kappa distribution has been subtracted. A post-hoc WSR non-parametric test is applied using a normal approximation method to test the equality of the measured data and the fitted Kappa distribution function. The test is applied to pairs of measurements (i.e. the same energy bin in the simulated kappa
distribution and in the ELS measurements) and is used to assess whether they are drawn from the same sample. The WSR test was chosen to assess the statistical significance primarily due to its suitability in testing paired data with small sample sizes. In this case, p-value > 0.05 indicates there are no statistically significant differences between the measured data and the fitted Kappa distribution. The p-values associated with the statistical tests for each of these fits indicates a good fit.

![Figure 3.5: Kappa distribution and subtraction from E9 and E19 data.](image)

**Figure 3.5:** Kappa distribution and subtraction from E9 and E19 data. **a)** Differential number flux spectrum of ELS data taken during Enceladus flyby E9 at 00:09:41 UT is shown in blue with a Kappa distribution fitting overlaid in red. **b)** Residual differential number flux after Kappa distribution contribution is subtracted. **c)** Differential number flux spectrum of ELS data taken during Enceladus flyby E19 at 09:31:29 UT is shown in blue with a Kappa distribution fitting overlaid in red. **d)** Residual differential number flux after Kappa distribution contribution is subtracted. The dashed line in each panel indicates the single count level of ELS.

### 3.4 Model

In order to investigate these electron populations a synthetic photoelectron production spectrum is constructed based on the modelling technique described by Schippers et al. [2009] to model photoelectrons in Saturn’s neutral torus. The method has been adapted to model the production of photoelectrons in the plume by choosing five dominant neutral species found within the Enceladus plume by INMS and their mixing ratios [Waite et al., 2017] found in Table 3.2.
Table 3.2: Composition of the Enceladus plume as determined by INMS [Waite et al., 2017].

<table>
<thead>
<tr>
<th>Enceladus plume composition</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O</td>
<td>97.5 %</td>
</tr>
<tr>
<td>H₂</td>
<td>0.90 %</td>
</tr>
<tr>
<td>NH₃</td>
<td>0.85 %</td>
</tr>
<tr>
<td>CO₂</td>
<td>0.55 %</td>
</tr>
<tr>
<td>CH₄</td>
<td>0.20 %</td>
</tr>
</tbody>
</table>

For each species we first calculate the rate coefficient, \( k \), (the rate at which photoelectrons are produced) in a given wavelength interval \( d\lambda \) using Equation 3.1.

\[
\text{Rate Coefficient} \quad k(\lambda) = \int_{\lambda_i}^{\lambda_i+\Delta\lambda_i} \Phi(\lambda) \sigma(\lambda) \, d\lambda \quad (3.1)
\]

Where \( \lambda \) is the wavelength, \( \sigma(\lambda) \) is the photoionisation cross section of the species and \( \Phi \) is the solar photon flux. The solar photon flux at Saturn \( \Phi(\lambda) \) (see Figure 3.6) and the photoionisation cross sections for each species in the model (see Figure 3.7) are taken from Huebner et al. [1992]). The rate coefficient as a function of \( \lambda \) can be calculated using Equation 3.1 and the result for each species is shown in Figure 3.8.

The final synthetic photoelectron production rate is then calculated for each species using Equation 3.2.

\[
R_i(\lambda) = k_i(\lambda)n_i \quad (3.2)
\]

Where \( n \) is the neutral species densities as measured by INMS in Waite et al. [2017] (see Table 3.2). The resulting synthetic spectrum corresponds to photoelectron production and does not include loss and transport processes. Due to the high neutral density in the plume, it is likely electron-neutral cooling is the main loss mechanism for these freshly produced photoelectrons. It is not expected that loss or transport processes will significantly alter the peak structure observed and so only the photoelectron source is considered in this simple model.

Figure 3.9 shows the modelled photoelectron production rate plotted against the excess energy \( E_e \) of the produced photoelectrons \( (E_e = hc/\lambda - \varphi) \), where \( \lambda \) is the photon
wavelength and \( \varphi \) is the species binding energy). As \( \text{H}_2\text{O} \) is the dominant neutral species in the plume, it is the overwhelmingly dominant source of photoelectrons in the model at almost all energies. The other species in the model (\( \text{CO}_2 \), \( \text{CH}_4 \), \( \text{H}_2 \) and \( \text{NH}_3 \)) contribute mostly towards broadening the peaks. Firstly, modelled peaks C (20–35 eV) and D (35–70 eV) are directly comparable to the peaks labelled C and D in Figure 3.4. The energy difference between these two sets of peaks is likely explained by spacecraft potential and analysis later in the chapter will correct for this offset. In addition to these two previously identified prominent peaks, there are three more peaks: A (6–10 eV), B (10–16 eV) and E (100–200 eV). A sharp reduction in photoelectron production above \( \approx 60–80 \text{ eV} \) is observed in the data. This is reminiscent of photoelectron observations made throughout the solar system [\textit{Coates et al.}, 2011].

Primarily considering the photoionisation reactions of the most dominant neutral contributor, \( \text{H}_2\text{O} \) (binding energies of 12.6 eV, 18.1 eV and 18.7 eV), the solar photon wavelength ranges responsible for each of the peak can be traced: Peak A (6–10 eV) is formed due to photoionisation by solar photons at wavelengths between 44–69 nm, Peak B (10–16 eV) by 36–56 nm photons, Peak C (20–35 eV) by 23–39 nm photons, Peak D (35–70 eV) by 14–23 nm photons and Peak E (100–200 eV) by 5.7–11 nm photons.

The other minor neutral species have similar binding energies and so they contribute

Figure 3.6: The solar photon flux propagated to 9.6 AU in the energy range 1–1000 eV. Figure generated from data provided in \textit{Huebner et al.} [1992].
3.4. MODEL

photoelectrons of similar wavelengths, only modified by a few nanometres.

![Graphs showing cross sections and rate coefficients for various molecules as a function of energy (eV).](image)

Figure 3.7: Photoionisation cross sections for neutral H₂, H₂O, CO₂, CH₄ and NH₃ as a function of energy (eV).

![Graphs showing rate coefficients for neutral H₂, H₂O, CO₂, CH₄ and NH₃ illuminated by solar UV photons at a distance of 9.6 AU as a function of energy (eV).](image)

Figure 3.8: Rate coefficient for neutral H₂, H₂O, CO₂, CH₄ and NH₃ illuminated by solar UV photons at a distance of 9.6 AU as a function of energy (eV).
Figure 3.9: Synthetic photoelectron production (cm$^{-3}$ s$^{-1}$) of H$_2$ in blue, H$_2$O in green, CO$_2$ in red, CH$_4$ in cyan, NH$_3$ in purple and overlaid in black is the total combined production versus excess energy $E_e$ ($E_e = h\nu / \lambda - \phi$, where $\lambda$ is the photon wavelength and $\phi$ is the threshold ionisation energy). Photoelectrons in the energy range shown are produced by the solar spectrum photons with wavelengths between $\approx$ 3–62 nm.
3.5 Analysis and Discussion

Photoelectron peaks are clearly observed at 16–30 eV (Peak C) and 30–60 eV (Peak D) across a variety of flybys with different encounter trajectories. We expect that the neutral composition encountered by the spacecraft may vary between encounter trajectories. This is because the plume and neutral torus neutral composition are subtly different (see Table 3.3) The plume contains a higher proportion of H$_2$O compared to the neutral torus, as the water has yet to be ionised into the water group molecules. For example, the spacecraft should encounter a larger proportion of ‘fresh’ plume material when encountering the Enceladus plume (on south passing trajectories) compared with trajectories which do not. This difference in neutral density will lead to different photoelectron spectrum, which may be detectable in the ELS data.

Table 3.3: Composition of the Enceladus plume as determined by INMS [Waite et al., 2017] compared with modelled density of the torus near Enceladus’ orbit [Jurac and Richardson, 2007].

<table>
<thead>
<tr>
<th></th>
<th>Enceladus</th>
<th>Neutral torus</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_2$O</td>
<td>97.5 %</td>
<td>49 %</td>
</tr>
<tr>
<td>H$_2$</td>
<td>0.90 %</td>
<td>24 %</td>
</tr>
<tr>
<td>OH</td>
<td>0</td>
<td>24 %</td>
</tr>
<tr>
<td>O</td>
<td>0</td>
<td>2 %</td>
</tr>
</tbody>
</table>

To investigate this, the electron data is averaged across the energetic particle shadow and a background kappa distribution is subtracted. Then the peak flux of peaks C and D is measured by fitting a Gaussian distribution to each peak using least squares regression. The ratio can then be calculated from these fits and the errors estimated by varying the manual fitting to find reasonable minimum and maximum fits.

Figure 3.10 shows the results of calculating the Peak C/D ratios for a variety of Enceladus flybys, plotting them all sorted by flyby trajectory. The error on measuring the intensity of each peak is large and there is no obvious relationship between plume encounter flybys and trajectories far from the plume. This suggests that any difference in photoelectron peak structure may be negligible at this distance from Enceladus or the data is simply too noisy to reveal it.
Figure 3.10: Flux ratio for peaks C (16–30 eV) / D (30–60 eV) for a selection of flybys with different flyby geometry.

3.5.1 Case studies

For this analysis, the modelled photoelectron production rate spectra (e.g. Figure 3.9) has been rebinned to match with ELS energy bins and scaled as to be comparable with the measured flux. The synthetic spectra is then potential shifted using estimates from the Radio and Plasma Wave Science instrument (RPWS) and compared with the Kappa subtracted ELS data (Figures 3.5b and 3.5d) Since transport and loss processes are not considered, the ELS electron spectra and the modelled photoelectron production rate can be compared qualitatively.

E9 and E19 Enceladus flybys are the best examples of plume photoelectron observations made by ELS throughout the mission so these are studied in further detail ahead. Other flybys which also encounter the Enceladus plume are less suitable due to other factors such as instrument orientation (negative ions and dust are observed in the ram direction) and closest approach distance.
3.5.1.1 E9

Figure 3.11: Kappa subtracted ELS data during E9 at 00:09:38 UT from anode 5 is shown in blue. Synthetic photoelectron production rate spectra shifted by RPWS spacecraft potential estimate and scaled to the ELS data is displayed in green. The dashed line indicates the single count level of ELS.

Figure 3.11 shows the results of overlaying the synthetic photoelectron production spectrum onto the subtracted ELS data from E9. The data are a 6 second average (three sweeps) from ELS anode 5, centred on 00:09:38 UT. Qualitatively, it can be seen that shifting the model by the RPWS spacecraft potential estimate provides a reasonable fit to the subtracted ELS data. Peaks A, B, C and D are all prominent in the subtracted data while there is no obvious structure in the 100–200 eV range (Peak E) and most flux here is likely to be noise.
3.5.1.2 E19

Figure 3.12: Kappa subtracted ELS data during E19 at 09:31:27 UT from anode 3 is shown in blue. Synthetic photoelectron production rate spectra shifted by RPWS spacecraft potential estimate and scaled to the ELS data is displayed in green. The dashed line indicates the single count level of ELS.

Figure 3.12 shows the results of overlaying the synthetic photoelectron production spectrum onto the subtracted ELS data from E19. The data are a 4 second average (two sweeps) from anode 3 centred on 09:31:29 UT, near the centre of the plume. The result of potential shifting the model by the RPWS estimate provides us with a good fit to subtracted data. There is evidence for peaks A, B, C and D while any data in the range of E (100–200 eV) is likely noise.
The fact that the fluxes are at times higher in the subtracted data than in the model at energies $\lesssim 10$ eV in both cases suggests that the Kappa fitting and subtraction may not be capturing the entire background population and some magnetospheric electrons still remain. Unfortunately, the Kappa high energy tail is relatively poorly constrained as the counts at energies $\gtrsim 100$ eV are close to (or below) the single count noise level of the instrument.

It is likely that additional disagreements between the data and model are in part due to the affects of source, transport and loss processes which are not considered. In the electron-impact ionisation process, a hot electron hits a neutral molecule and two electrons are emitted: a cold electron (a few eV) and a warm electron (energy lower than the original impacting electron). Compared to photoionisation, the cross sections for electron-impact ionisation result in a much broader electron energy spectrum. Due to the relative lack of hot electrons in the energetic particle shadow and broad spectrum produced, it is considered unlikely that electron-impact ionisation affects the observed peak structure significantly even if the total flux contribution is large.

Although the model only considers photoelectron production rates, it appears that the multiply-peaked structure observed in the subtracted ELS data can be explained by photoelectrons produced in the plume neutrals surrounding Enceladus. There is evidence for Peaks A (3–6 eV), B (7–11 eV), C (16–30 eV) and D (30–60 eV) at both E9 and E19. There is also some evidence for a Peak E at 100–200 eV in longer averages, though at much lower count rates and often close to the noise level of the instrument (not shown here).
3.6 Conclusions and Summary

The negatively charged particle environment near Enceladus consists of several populations: magnetospheric electrons, photoelectrons, cluster ions and charged ice grains. Peaks at $\approx 16$–30 eV and $\approx 30$–60 eV have previously been identified using CAPS-ELS data both in the plume of Enceladus [Coates et al., 2013; Ozak et al., 2012] and the inner magnetosphere [Schippers et al., 2009; Cravens et al., 2011]. Both populations are observed unambiguously during all of the Enceladus flybys during which the instrument is oriented away from the ram direction. During ram-oriented flybys, there is still evidence of photoelectron signatures but much of the detail is obscured by negative ions and dust grain impacts.

By first subtracting the magnetospheric electron population, it is possible to identify a series of electron peaks in the low-energy range ($<100$ eV) of ELS electron spectra during Enceladus flybys E9 and E19. These peaks include previously unidentified structure at energies $\lesssim 20$ eV.

The region is populated by both magnetospheric photoelectrons (primarily from the neutral torus) and by plume photoelectrons. Due to the comparatively high density in the plume, we expect the plume region where the data in this study originates to be dominated by photoelectrons produced from plume neutrals. By comparing the data to a synthetic photoelectron production model based on plume neutral densities, it is concluded that this structure can be explained by photoelectrons created by the photoionisation of neutrals being emitted in the plumes of Enceladus.

It is found that RPWS spacecraft potential estimates are sufficient to align the peaks predicted by the model and those revealed in the data using Kappa subtraction. Spacecraft potential estimates made using ELS data from Titan’s ionosphere [Coates et al., 2007b; Desai et al., 2017] and the inner magnetosphere [Schippers et al., 2009] have found differences between ELS and RPWS potentials of $\approx -2$–0.5 V. A possible explanation for this discrepancy is differential charging on the spacecraft caused by variations in the conductivity of surfaces on different parts of the spacecraft [Crary
et al., 2009]. Due to the limited resolution of ELS and the broadness of these peaks in this environment, it is impossible using this method to conclude whether or not these differences exist for this data. With a more sophisticated model and better energy resolution, future missions may be able to take advantage of this technique to accurately assess the spacecraft potential using photoelectrons peaks.

All of these photoelectrons being produced in the Enceladus plumes and surrounding neutral torus contribute to the total ‘hot’ electron population. Using 3D moment electron densities calculated using the method outlined in Lewis et al. [2008], it is estimated that the ‘hot’ (> 15 eV) to ‘cold’ (< 15 eV) electron density ratio is ≈ 0.1–0.5%. This ratio is important for informing magnetospheric models, especially of the inner magnetosphere (e.g. Fleshman et al. [2012]).

In summary:

- Modelled plume photoelectron production using solar spectrum, photoionisation rate coefficients and plume neutral densities and cross sections.
- Revealed a complex low energy peak structure including two previously unreported photoelectron peaks.
- Qualitatively show this peak structure may be explained by the presence of photoelectrons produced from the the Enceladus plume neutrals.
In this chapter, observations of photoelectrons in the shadow of Saturn are presented and analysed. A geometric model of Saturn’s shadow is constructed and used to assess the feasibility of potential photoelectron sources and transport mechanisms. This chapter attempts to explain the unexpected observations of photoelectrons in shadow and analyse transport mechanisms which may explain their presence.
4.1 Introduction

In 1992, Hubble Space Telescope (HST) observations showed that Saturn’s inner magnetosphere is dominated by neutrals [Shemansky et al., 1993]. The source of which was revealed by Cassini some 14 years later to be the plumes of Enceladus [Dougherty et al., 2006; Porco et al., 2006]. The neutral molecules spread throughout the region forming a dense neutral torus, the density of which exceeds the plasma density by at least a factor of 10 [Richardson, 1998]. Simulations have shown how the dominant species of the neutral torus (H₂O, H, OH and O) are distributed throughout the inner magnetosphere [Jurac et al., 2002; Jurac and Richardson, 2005, 2007]. Figure 4.1 reproduces neutral densities from the Jurac and Richardson [2005] model and an extra panel showing a total neutral density calculated by summing the contributions from each four dominant species. The neutral density peaks around the orbit of Enceladus (3.95 \(R_S\)) and drops off significantly at \(\approx 2.5 \ R_S\) as the neutrals are absorbed by the rings.

When the neutrals in this torus are illuminated by EUV photons from the Sun, photoelectrons are produced at characteristic energies depending on the species of the neutral and the energy of the incoming photon (see Section 1.2). Characteristic peaks at \(\approx 20 \text{ eV}\) and \(\approx 45 \text{ eV}\) have been observed by Cassini at all L-shells inside 4–5 [Schipper et al., 2009]. Photoionisation is also a key source of photoelectrons within Saturn’s ionosphere. Ionisation of hydrogen is the dominant source of plasma at low latitudes [Cravens et al., 2018; Galand et al., 2009]. Ionospheric photoelectrons have been observed directly at Earth [Coates et al., 1985], Venus [Coates et al., 2008], Mars [Frahm et al., 2006] and Titan [Cravens et al., 2005; Coates et al., 2007a; Wellbrock et al., 2012]. Many of these observations have been made at several planetary radii distance and show how these electrons are able to escape along magnetic field lines into the magnetosphere.

During Cassini’s 13 years at Saturn, the spacecraft crossed directly into the shadow of the planet and its rings on many occasions. Since the production of photoelectrons relies on incident sunlight, these large regions of darkness have a big impact on total ionisation in the magnetosphere.
Figure 4.1: Modelled neutral densities (cm$^{-3}$) in Saturn’s inner magnetosphere for H$_2$O, OH, H, O and total combined neutral density. Figure generated from the Jurac and Richardson [2005] neutral density model.
4.2 Modelling Saturn’s Shadow

In order to analyse the effect of Saturn’s shadow on the magnetosphere, it is necessary to model the three-dimensional shape of Saturn’s shadow projected through space.

4.2.1 Influencing Factors

There are a number of factors to consider when building a geometrical model of Saturn’s shadow which are discussed in the following sections.

4.2.1.1 Saturn’s Shape

While gravity pulls Saturn into a spherical shape, its fast rotation distorts the sphere into an oblate spheroid. Equation 4.1 describes this shape in Cartesian coordinates.

\[ \frac{x^2 + y^2}{a^2} + \frac{z^2}{c^2} = 1 \]  

(4.1)

Where \( a \) is the equatorial radius and \( c \) is the polar radius. Figure 4.2 shows the shape of an oblate spheroid as described by Equation 4.1.

For Saturn:

\[ a = R_{\text{equatorial}} = 60268 \text{ km} = R_S \]
\[ c = R_{\text{polar}} = 54364 \text{ km} \approx 0.90 R_S \]

Figure 4.2: Diagram showing an oblate spheroid in cartesian coordinates as described by Equation 4.1. Image credit: Wikimedia Commons.
4.2. MODELLING SATURN’S SHADOW

4.2.1.2 Sun-Saturn Angle

Saturn’s orbit is inclined by 2.5° to the ecliptic and it has an axial tilt relative to the ecliptic of 26.7° [NASA’s Planetary Factsheet - Saturn]. This means that throughout the Saturnian year, the relative angle between the Sun and Saturn’s equatorial plane ($\theta_{SS}$) varies by $\approx 55$–60°. In Saturn’s frame of reference, a positive $\theta_{SS}$ means the Sun lies below the equatorial plane and above for a negative value.

Cassini arrived at Saturn in July 2004, just after the northern winter solstice ($\approx 1.5$ years). At this time, $\theta_{SS}$ was at the largest positive value for the entire mission at 27°. Cassini was at Saturn to observe during vernal equinox on 11th August 2009. The Sun was directly above Saturn’s equator and the rings appeared unusually dark as the incident light was almost parallel to the thin rings (Figure 4.3). As Cassini completed its mission in September 2017, Saturn had just passed northern summer solstice and $\theta_{SS}$ was at its largest negative value of -30°.

Figure 4.4 shows how $\theta_{SS}$ varied over $\approx \frac{1}{2}$ a Saturnian year while Cassini was operating at Saturn. Since $\theta_{SS}$ varies significantly over time, the direction in which Saturn casts its shadow also varies. Throughout this model, ephemeris data obtained from the JPL HORIZONS system is used to calculate $\theta_{SS}$.

Figure 4.3: Image of Saturn at equinox, captured by Cassini in August 2009. Image credit: Cassini Imaging Team, ISS, JPL, NASA, ESA.
Figure 4.4: Diagram showing how the relative angle between the Sun and Saturn’s equatorial plane ($\theta_{SS}$) varied over the $\approx \frac{1}{2}$ Saturnian year during which Cassini operated at Saturn. The $X$ direction is parallel with Saturn’s equatorial plane, $Z$ is along the rotation axis of Saturn. The orange arrow points towards the direction of the Sun. The shaded region represents the shadow cast by Saturn. The dotted shows the position of Saturn’s magnetic equator.
4.2. MODELLING SATURN’S SHADOW

4.2.2 Geometry of the Shadow

By considering the factors described in Section 4.2.1, the important properties of the shadow geometry can be described.

4.2.2.1 Projection Shape

The geometrical shape of a shadow cast by any object under incident parallel light can be thought of as a prism. The cross-section of this prism is the 2D projection of the object onto a plane perpendicular to the incident light direction. A sphere is axisymmetric about 3 axes so the 2D projection is circular from any direction and the shadow is cylindrical. An oblate spheroid is axisymmetric about 1 axis (Z direction) and the 2D projection is an ellipse, the ellipticity of which depends on the projection angle relative to the XY plane.

The projection ellipse of an oblate spheroid onto a plane at an angle $B$ to the $XY$ plane has a semi-major axis $a'$ equal to the equatorial radius $a$ of the oblate spheroid. Equation 4.1 describes the semi-minor axis $c'$ of the projection ellipse (see Appendix A for derivation).

$$c' = a\sqrt{\left(\frac{c}{a}\right)^2 \cos^2 B + \sin^2 B}$$  (4.2)

When considering Saturn, the projection angle $B$ is analogous to planetocentric latitude. Using this formula the 2D projection ellipse and therefore, the cross-sectional shape of Saturn’s shadow can be calculated for any given latitude. Figure 4.5 shows how the projected shape of Saturn changes with latitude (north or south). When viewed from the equator (0° latitude), the projection is an ellipse with semi-major and semi-minor axes equal to $R_{\text{equatorial}}$ and $R_{\text{polar}}$ respectively. As the viewing angle increases, the projection becomes more circular until reaching 90° latitude (over the pole) where the projection is a perfect circle with radius $R_{\text{equatorial}}$. 
Figure 4.5: Diagram showing how the projected shape of Saturn varies with viewing latitude. The X direction is parallel with the equator, Z is parallel with the rotation axis. For reference, a dashed line indicates 1 $R_S$ from the centre (Saturn’s equatorial radius) for each axis. 0° latitude shows the projection as seen from the equator, 90° shows the projection from above the pole.
4.2. MODELLING SATURN’S SHADOW

4.2.2.2 Terminator Shape

The terminator is the line which divides the day and night side of a planetary body. It is defined as the locus of points where the line through the parent star is tangent. For bodies without an atmosphere, the terminator forms a solid line between night and day. On atmospheric bodies, the terminator is fuzzier due to light being scattered from beyond the horizon.

The Earth has an axial tilt of 23.5°, meaning the path of the terminator varies throughout the year. This means the poles receive varying amount of daylight on a seasonal basis. Saturn’s axial tilt (26.7°) is similar to Earth’s and so experiences the same annual variations. Figure 4.6 shows the central location of the terminator at winter solstice, vernal equinox and summer solstice. In reality, Saturn’s atmosphere scatters light and produces a less well-defined terminator than the one shown with this model.

![Figure 4.6: Diagram showing the central position of the terminator viewed from above the north pole (top panels) and above the south pole (bottom panels) at different times in the Saturnian year.](image)
4.2.3 Additional Modelled Features

In addition to the geometries of the shadow and terminator, several other features have been included to build up a more complete picture (Figure 4.7).

Neutral Densities

The first of these are densities from the neutral torus. The total neutral density from Figure 4.1 is added using the same colour scale and contours for all densities up to 50 cm$^{-3}$ (5% peak density).

Magnetic field model

The next feature added is a representation of Saturn’s magnetic field. Since the region of interest is within $\approx 4–5 R_S$, a dipolar approximation is reasonable. In polar coordinates, dipolar magnetic field lines satisfy Equation 4.3.

$$r(\theta) = L \cos^2 \theta$$  \hspace{1cm} (4.3)

Where $L$ is L-shell (the radius of the field line at the magnetic equator).

Saturn’s magnetic equator is offset by 0.0466 $R_S$ (2808.5 km) northwards along the spin axis, parallel with the equatorial plane [Dougherty et al., 2018].
4.2. MODELLING SATURN’S SHADOW

4.2.4 Example Geometry Plots

Figure 4.7: Plot showing the modelled shadow geometry and Cassini’s trajectory through it on 21st May 2005. Panel a shows the perspective from the shadow entry point. Panel b shows the perspective from the shadow exit point. For each panel, Cassini’s trajectory is shown in blue with markers along indicating shadow crossings (see key below). A blue arrow indicates the direction the spacecraft travelled along this trajectory. The vertical dashed line in the left hand panels indicates the YZ cross-section plane shown in the right hand panels. The coloured contours show a representation of total density in the neutral torus using the same format as Figure 4.1 (contours from 50–1000 cm$^{-3}$). The dotted horizontal line and curved dashed lines indicate the position of Saturn’s magnetic equator and show dipolar magnetic field lines. Indicated are the directions of (geographic) north and plasma flow (same direction as planet rotation).

▲ Cassini crossing into Saturn’s shadow
▼ Cassini crossing out of Saturn’s shadow
▶ Spacecraft magnetic footpoint crossing terminator into nightside
▼ Spacecraft magnetic footpoint crossing terminator into dayside
4.2.4.1 Assumptions and Limitations

When constructing this model, a number of key assumptions and simplifications are made which affect its accuracy:

**Point source Sun**

Considering the Sun to be an infinitely distant point source means incoming light can be treated as parallel, simplifying calculation of the shadow geometry. In reality, the Sun is of course a distributed source a finite distance from Saturn. This means the shadow cast by Saturn in fact has three components to it: the umbra, penumbra and antumbra. Figure 4.8 labels these components in Earth’s shadow. Like Earth’s, the shadow of Saturn will contain regions of partial shadow (penumbra and antumbra) around the edges and not a sharp boundary. Opposite edges of the shadow will also be diverging as the incoming light is not exactly parallel.

It is estimated that neither of these assumption introduce a significant amount of error (< 1%) on calculation of the shadow geometry throughout the region we are interested in.

*Figure 4.8:伞影、半影和远影的示意图。在这些区域可能会看到一些图像 (注: 尺寸和距离不按比例尺)。图像来源: Wikimedia Commons.*
4.2. MODELLING SATURN’S SHADOW

Rings

This model does not include shadowing from the rings although it likely contributes significantly to the total shadowing effect on Saturn’s magnetosphere. Building a model of the rings is more complicated than for Saturn for several reasons. Firstly, the 3D shape of the ring is mathematically more complicated to project a shadow through space. Secondly, the rings are not of uniform opacity and this must be accounted for as a partial shadow. Finally, the rings have finite thickness and so the mean free path at small angles must be considered. There are likely many more complications not listed here.

As a result ring shadowing was considered to be too complex to implement into this study. The events considered here are entirely shadowed regions caused by the body of Saturn although the effect of ring shadowing is often visible in the data at times preceding and following the main shadow event.

Atmospheric effects

Here on Earth, atmospheric refraction is responsible for the twinkling of the stars and delays the apparent setting of the Sun by \(\approx 5\) minutes. At Saturn, atmospheric refraction will bend light into the shadow, causing partial illumination into the area obscured by the Saturn. This will also affect the ring shadow as the ring has an exosphere [Coates et al., 2005; Tokar et al., 2005; Waite et al., 2005].

As the ‘surface’ of Saturn is not a solid boundary, there will also be a diffusion of the light through the atmosphere close to the edges. In this model, the ‘surface’ of Saturn is considered to be at the 1 bar pressure level and is treated like a solid boundary with opacity stepping from 0 to 1 at the surface. Neither of these effects are estimated to have a large impact on the shadow geometry through the region we are interested in.
4.3 Observations

During the time CAPS was actively collecting data, shadow events were recorded during 74 orbits (see Table B.1). A shadow crossing event is simply defined as any time the spacecraft passes into the shadow of Saturn or the rings. These events almost always occur close to periapsis ($\lesssim 8 R_S$). This is because Cassini is close to the equatorial plane and the shadow’s angular size is larger closer in, maximising the chances of a shadow encounter. There are two notable exceptions where the spacecraft was near apoapsis. The first on 15th September 2006 occurred when Cassini was at $\approx 38 R_S$, lasting around 14 hours. During this time, Cassini captured a series of images which combined to form Figure 4.9. A similar mosaic included at the beginning of this chapter was formed from images taken during the second of these distant shadow crossings in an event NASA calls ‘The Day the Earth Smiled’. Members of the public were encouraged to smile and wave towards Saturn as Cassini captured the images of Saturn with Earth just a tiny dot in the background.
4.3. OBSERVATIONS

4.3.1 Typical Features

The effect of the spacecraft entering the shadow is visible in the charged particle data for every event. Figure 4.10 shows an electron and ion spectrogram for a typical shadow event. Marked on this plot are the times where Cassini is in shadow, as recorded using NASA’s eyes on the solar system software (see Appendix B).

In Figure 4.10a there is an apparent electron density drop (at energies $<30\,\text{eV}$) which coincides with the onset of Saturn’s shadow. While not as visible, the density increases again as the spacecraft enters sunlight again.

During the first ring shadow, this same density drop is also visible. Since the opacity of the ring varies, the density drop also changes across the encounter. The temporary recovery of the electron density in the middle of the encounter is due to the Encke Gap in Saturn’s A ring. The second ring shadow signature is much less obvious. This is because the data is overwhelmed with an increase in injection events and hot plasma as the spacecraft L shell increases from around 4.3 at shadow onset to almost 7 as sunlight returns.

Figure 4.10b shows an apparent energy shift in the ion distribution on encountering the shadow. The ion distribution reacts more slowly to the shadow boundary than the electron distribution.

This pattern of a reduction in electron energy flux and a shifting of the ion distribution is consistent with sudden change in spacecraft potential (see Figure 2.8). Spacecraft photoelectrons produced by incident sunlight is an important factor in the balance of spacecraft potential (see Section 2.5 and references therein). Therefore it is reasonable to expect a spacecraft potential shift when that source is ‘switched off’ in the shadow. Further analysis of the spacecraft potential changes when Cassini is shadowed are explored in Chapter 5.
Figure 4.10: Spectrogram plots showing ELS and IMS data from the shadow event on 3rd May 2005. The times when Cassini is in the shadow of the rings and of Saturn itself are indicated above the plot. a) ELS electron energy spectrogram in DEF. b) IMS ion energy spectrogram in DEF. N.B. Y axis energy scale is reversed (lowest energy at the top).
4.3.2 Photoelectron Observations

Less typical features are observations of magnetospheric photoelectrons in the shadow. Of the 74 events listed, there are photoelectron signatures while the spacecraft (and surrounding plasma) is in shadow during 17 events (see Table 4.1). The majority of these are during the partial ring shadow and so some local photoionisation may still be possible. On the 24th October 2007, photoelectrons are visible throughout the absolute shadow of Saturn. Photoelectrons are observed (mostly during ring shadow) even when Enceladus is relatively distant from the shadow, indicating that the neutral torus remains dense enough throughout to produce photoelectrons.

Evidently these photoelectrons cannot be produced locally deep inside the shadow. They must be produced at a sunlit source and transported into the shadow. There are three potential source and transport options available to investigate:

- Produced in sunlit neutral torus at earlier local times and corotate into the shadow
- Produced in sunlit ionosphere and travel along field lines to the spacecraft in the shadow
- Produced in sunlit neutral torus north or south of the shadow and travel along field lines to the spacecraft in shadow

Presented in the next sections are data from two shadow events. The first is the clearest example of photoelectron observations which are visible in the shadow of Saturn. The second is a example of a similar shadow event during which the proposed photoelectrons sources above are not viable and so no photoelectrons are observed.
Table 4.1: Summary of photoelectron observations during shadow events. In the event type column, the shadows encountered by the spacecraft on its trajectory are listed in order. S represents the shadow of Saturn, R the shadow of the rings and – represents gaps of direct sunlight between them. The location of Enceladus is indicated by local time (LT). For reference, all these encounters occur at approximately midnight (00:00). See Table B.1 for more information on these events.

<table>
<thead>
<tr>
<th>Date</th>
<th>Event type</th>
<th>Trajectory direction</th>
<th>Persistence</th>
<th>L-shell range</th>
<th>Enceladus local time (LT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01 Jul 2004</td>
<td>S</td>
<td>Outbound</td>
<td>Partial</td>
<td>1.82–2.41</td>
<td>09:36</td>
</tr>
<tr>
<td>15 Apr 2005</td>
<td>R</td>
<td>Outbound</td>
<td>Persistent</td>
<td>2.76–3.39</td>
<td>11:06</td>
</tr>
<tr>
<td>21 May 2005</td>
<td>R-S</td>
<td>Outbound</td>
<td>Fade out</td>
<td>4.30–6.98</td>
<td>00:04</td>
</tr>
<tr>
<td>11 Jun 2007</td>
<td>R-S</td>
<td>Inbound</td>
<td>Fade in</td>
<td>4.93–3.11</td>
<td>08:27</td>
</tr>
<tr>
<td>19 Dec 2007</td>
<td>R-S</td>
<td>Inbound</td>
<td>Fade out</td>
<td>3.99–3.12</td>
<td>05:05</td>
</tr>
<tr>
<td>27 Jan 2008</td>
<td>R-S</td>
<td>Inbound</td>
<td>Fade out</td>
<td>3.96–3.39</td>
<td>03:02</td>
</tr>
<tr>
<td>02 Mar 2008</td>
<td>R-R</td>
<td>Inbound</td>
<td>Persistent</td>
<td>4.36–4.03</td>
<td>03:36</td>
</tr>
<tr>
<td>19 Aug 2008</td>
<td>R-R</td>
<td>Inbound</td>
<td>Persistent</td>
<td>4.05–3.96</td>
<td>07:04</td>
</tr>
<tr>
<td>02 Sep 2008</td>
<td>R-R</td>
<td>Inbound</td>
<td>Persistent</td>
<td>4.08–3.99</td>
<td>01:22</td>
</tr>
<tr>
<td>10 Sep 2008</td>
<td>R-R</td>
<td>Inbound</td>
<td>Persistent</td>
<td>4.07–3.98</td>
<td>10:35</td>
</tr>
<tr>
<td>25 Sep 2008</td>
<td>R-R</td>
<td>Inbound</td>
<td>Persistent</td>
<td>4.05–3.98</td>
<td>04:51</td>
</tr>
<tr>
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<td>R</td>
<td>Inbound</td>
<td>Persistent</td>
<td>4.05–3.98</td>
<td>14:05</td>
</tr>
<tr>
<td>17 Oct 2008</td>
<td>R</td>
<td>Inbound</td>
<td>Persistent</td>
<td>4.04–3.97</td>
<td>06:53</td>
</tr>
</tbody>
</table>
4.3.3 Photoelectrons in Shadow - 24\textsuperscript{th} October 2007

![Summary plot showing Cassini data from the shadow event on 24\textsuperscript{th} October 2007.](image)

Figure 4.11: Summary plot showing Cassini data from the shadow event on 24\textsuperscript{th} October 2007. Indicated along the top of the plots are the times when Cassini is being shadowed by Saturn’s Rings and the body of Saturn. Each panel shares a common X axis of time in UT along the bottom. CAPS data has been penetrating radiation subtracted. a) ELS Electron energy spectrogram in DEF. b) IMS Ion energy spectrogram in DEF. N.B. Y axis energy scale is reversed (lowest energy at the top). c) Cassini distance from Saturn centre (in $R_S$) and spacecraft L-shell. d) Pitch angle in degrees of electrons measured by each ELS anode. e) ELS 3D moments, electron density ($m^3$). f) Magnetic field (nT) in Spacecraft coordinates.
Cassini encountered the southern edge of Saturn’s shadow on the 24\textsuperscript{th} October 2007, towards the end of Cassini’s primary mission phase. Between approximately 5:05 and 6:17, the spacecraft spent $\approx 72$ minutes in darkness. The encounter happened during the inbound section on approach just a few hours before periapsis.

Figure 4.11 shows a summary of data gathered by the CAPS and MAG instruments during the shadow event. The periodicity seen in the CAPS panels is caused by the actuation of the instrument. Panels a and b show the electron and ion spectra respectively. Prominently visible throughout the electron spectrogram is a photoelectron peak at $\approx 20$ eV. Panel c shows the L-shell of the spacecraft over time. The L-shell varies between $\approx 4.33–3.99$. Panels d and e show the ELS pitch angle per anode and calculated 3D electron density moment respectively. Panel f shows magnetic field data from the MAG instrument.

**Figure 4.12:** Plot showing photoelectron peaks throughout the shadow on 24\textsuperscript{th} October 2007. a) CAPS-ELS electron spectrogram for the event with five times marked with coloured dots below white dashed lines. b) 60 s time averages starting at each of the marked times plotted in the same colour as the dots shown in the previous panel.
4.3. OBSERVATIONS

Figure 4.12 shows an electron spectrogram and a series of time averages at different times throughout the shadow event. As can be seen in the spectrogram, the time average plots in panel b show the same characteristic photoelectron peaks observed in many planetary environments previously. Although the absolute flux of these peaks increases with time, this is likely due in part to the increasing background penetrating radiation. The electron density drop at low energies between the sunlit and shadowed spectra is also evident.

Figure 4.13: CAPS-ELS energy spectrogram plotted against L-shell from shadow event on 24th October 2007. The data has been penetrating radiation subtracted.

Figure 4.13 shows the ELS spectrogram plotted against L-shell. It clearly shows the photoelectron signature fading with increasing L-shell. It has almost completely faded when the L-shell reaches \( \approx 5.2 \). This correlates well with the radial extent of the densest part of the neutral torus (Figure 4.1): the presumed source of these photoelectrons.
Figure 4.14: Plot showing the modelled shadow geometry and Cassini’s trajectory through it on 24th October 2007. **a)** Geometry perspective from the shadow entry point. **b)** Geometry perspective from the shadow exit point. The thicker part of the blue trajectory line indicates when photoelectron signatures are seen in ELS data. See Figure 4.7 caption for further details.
Figure 4.14 shows the geometry of the shadow event on 24th October 2007. The inclination of the orbit is small and the spacecraft stays close to the equatorial plane throughout the event. The event occurs during the northern hemisphere winter and so the the Sun lies below the equatorial plane and the shadow is angled northwards. Cassini’s trajectory is shown in blue with the direction of travel indicated by arrows. The thicker part of the trajectory indicates where photoelectron signatures have been identified in ELS data. The \( XZ \) plot at approximately \( X = 3–4.5 \, R_S \) indicates that while the neutral torus is in shadow at the equator, a significant proportion of the densest part remains sunlit to the south.

![Figure 4.14](image)

**Figure 4.15:** Plot showing spacecraft attitude and ELS electron pitch angle information from the shadow event on the 24th October 2007. **a)** Spacecraft attitude over time in spacecraft coordinates. **b)** ELS electron energy spectrogram. The typical drop in electron flux during shadow can be seen towards the centre of the plot. **c)** ELS electron flux in the 22 eV energy bin mapped onto the pitch angle measured by anode 5. The horizontal dashed line in panel b indicates the 22 eV energy bin.

Figure 4.15 shows ELS electron pitch angle information at 22.21 eV, the energy bin where photoelectron observations tend to peak. The spacecraft makes only small attitude changes throughout the shadow event (centre of the plots). The orientation of the
spacecraft means that anode 5 has good and stable pitch angle coverage. Figure 4.15c shows no clear pitch angle bias at this energy, suggesting a local source for the photoelectrons.

Figure 4.16 shows the path of the spacecraft’s magnetic footprint mapped onto the ionosphere at 2000 km at both poles. Although the Sun-Saturn angle means more of the south pole is illuminated, the footprint of the spacecraft on the ionosphere is clearly shadowed for a significant amount of time before and after the shadow event.

Figure 4.16: Plot showing the position of the day-night terminator at 2000 km at Saturn’s poles and the path of Cassini’s magnetic footprint during the shadow event on 24th October 2007. The top panel shows perspective looking down on the north pole of Saturn. The bottom panel shows the perspective looking down on the south pole. The markers used are the same as used in previous geometry plots, see the caption of Figure 4.7 for more information.
4.3.4 Photoelectron Absence at Equinox - 19th June 2010

![Summary plot showing Cassini data from the shadow event on 19th June 2010. Indicated along the top of the plots are the times when Cassini is being shadowed by Saturn’s Rings and the body of Saturn. Each panel shares a common X axis of time in UT along the bottom. a) ELS Electron energy spectrogram in DEF. b) IMS Ion energy spectrogram in DEF. N.B. Y axis energy scale is reversed (lowest energy at the top). c) Cassini distance from Saturn centre (in RS) and spacecraft L-shell. d) Pitch angle in degrees of electrons measured by each ELS anode. e) ELS 3D moments, electron density (m^3). f) Magnetic field (nT) in Spacecraft coordinates.](image-url)
Closer to equinox in August 2009, the shadow event on 19\textsuperscript{th} June 2010 presents an opportunity to investigate the unique circumstances of equinox where the Sun-Saturn angle is small. The spacecraft orbit is close to equatorial and crosses through the shadow relatively close to centre. Between approximately 0:17 and 3:11, the spacecraft spent $\approx 174$ minutes in darkness. The encounter happened during the inbound section of the orbit.

Figure 4.17 shows a summary of data gathered by the CAPS and MAG instruments during the shadow event. The periodicity seen in the CAPS panels is caused by the actuation of the instrument. Panels a and b show the electron and ion spectra respectively. Panel c shows the L-shell of the spacecraft over time. The L-shell varies between $\approx 5.82$–$4.10$. Panels d and e show the ELS pitch angle per anode and calculated 3D electron density moment respectively. Panel f shows magnetic field data from the MAG instrument.

![CAPS-ELS energy spectrogram plotted against L-shell from shadow event on 19\textsuperscript{th} June 2010. The data has been penetrating radiation subtracted.](image-url)
4.3. OBSERVATIONS

(a) Shadow entry perspective (marker = ▲).

(b) Shadow exit perspective (marker = ▼).

Figure 4.19: Plot showing the modelled shadow geometry and Cassini’s trajectory through it on 19th June 2010. a) Geometry perspective from the shadow entry point. b) Geometry perspective from the shadow exit point. The thicker part of the blue trajectory line indicates when photoelectron signatures are seen in ELS data. See Figure 4.7 caption for further details.
Figure 4.20: Plot showing the position of the day-night terminator at 2000 km at Saturn’s poles and the path of Cassini’s magnetic footprint during the shadow event on 19th June 2010.

Figure 4.20 shows the path of the spacecraft’s magnetic footpoint mapped onto the ionosphere at 2000 km at both poles. The footpoint of the spacecraft on the ionosphere is again clearly shadowed throughout the shadow entire event and for a significant time either side.
4.4 Discussion

Photoelectrons in shadow

During the shadow event on the 24th October 2007, photoelectrons are observed the entire time the spacecraft is close to equator and therefore, inside the densest part of the neutral torus. Figure 4.16 shows that the magnetic footpoint of the spacecraft in the ionosphere remains in shadow throughout the photoelectron observations. Figure 4.15 shows no significant pitch angle preference during the shadow event. This suggests a relatively local source since the pitch angle distribution is large. Photoelectrons from a distant source (e.g. the ionosphere) would be field-aligned. Therefore it is considered unlikely these photoelectrons are ionospheric in origin.

Inspecting the \(XZ\) and \(YZ\) panels of Figure 4.14 reveals a significant proportion of the neutral torus remains in sunlight event during the shadow event. A magnetic connection from the spacecraft through this dense sunlight region may be responsible for transporting freshly produced photoelectrons northwards into the shadow, where they are observed by the spacecraft.

Absence of observations

The shadow event on the 19th June 2010 is one example of a shadow event during which photoelectrons are not observed, despite relatively similar conditions. Figure 4.20 shows that like other shadow events, the spacecraft ionospheric footprint remains in shadow throughout the event, so no ionospheric photoelectrons should be expected. There is no evidence of photoelectron signatures during the shadow in or for the rest of the inbound section of the orbit (Figure 4.18). It is not until the outbound section on the dayside where the photoelectron signature returns.

As this shadow event is closer to Saturn’s vernal equinox (August 2009), the Sun-Saturn angle is smaller (Figure 4.19). Therefore a higher proportion of the neutral torus is shadowed and only regions of 2–5% peak neutral density remain sunlit. Cassini enters the shadow at \(\approx 5.82 R_S\), which is too far out to reliably expect to see a photoelectron signature. However, by the end of the event the spacecraft is well within the region
where photoelectrons may be expected. The lack of a significant sunlit and magnetically connected source is considered the primary reason why photoelectrons are not observed during this time despite otherwise favourable conditions.

4.5 Conclusions and Summary

In this chapter, observations of photoelectrons inside the shadow of Saturn are presented and potential sources for these photoelectrons are explored and discussed. Unlike other photoelectron observations made at Saturn [Coates et al., 2005; Schippers et al., 2009; Ozak et al., 2012; Coates et al., 2013; Taylor et al., 2018], these are unique in that they are observed during complete shadow and the possibility of local production is completely ruled out. These observations are most similar to those seen near Titan where the local neutral density is too low to support local production [Coates et al., 2007a; Wellbrock et al., 2012]. When there is no local source possible (i.e. a lack of neutrals or sunlight), it must be concluded that the photoelectrons are being transported to the observation location. This study sought to analyse and consider possible remote photoelectron sources and the transport mechanisms which could bring them into the shadowed observation locations.

For most of the Saturnian year, field lines passing through the shadow of Saturn are also shadowed at their intersection with the ionosphere at both poles. This makes it unlikely that observations of photoelectrons in the shadow of Saturn and the rings (or for most local times on the nightside) are ionospheric in origin. However, near the solstice when the Sun-Saturn angle is most extreme (Figure 4.4) it is possible that the ionospheric intersection of low L-shell field lines may be sunlit at one pole at all local times (Figure 4.6). Unfortunately, no CAPS-ELS data are available close to Saturn’s Summer solstice in May 2017 (the only solstice observed by Cassini) and so the opportunity to potentially observe transported ionospheric photoelectrons in the shadow was missed.

As the only remaining option, the sunlit neutral torus is considered to be the source of these photoelectron observations. It has been shown that a significant proportion of the neutral torus can remain in sunlight throughout most of the year and these sunlit
regions may be magnetically connected through the shadow (Figure 4.14).

These observations (and lack thereof) hint at wider seasonal effects driven by the variation of Saturn’s complex shadowing geometry. Along with electron impact ionisation, photoionisation of the neutral torus contributes significantly to the total ionisation in Saturn’s magnetosphere [Gombosi et al., 2009]. At equinox, the densest part of the neutral torus is in shadow surrounding midnight local time (see Figure 4.4). It is estimated that up to $\approx 10\%$ of the total torus between 3–4 $R_S$ is in shadow at all times at equinox. Half a Saturn year later at solstice, the dense part of the neutral torus is sunlit at all local times. This annual variation in the amount of sunlight received by the neutral torus may result in a greater plasma contribution from photoionisation during the solstice compared to at equinox.

There is no evidence for photoelectrons in Saturn’s shadow after the 31st October 2008 event. This may be due to a change in the spacecraft trajectory orientation during the Cassini Equinox mission phase which meant shadow crossings tended to occur at L-shells too high to expect photoelectron observations (see Table B.1). For the handful of events which do occur at appropriate L-shells for observation, it is considered likely that the low Sun-Saturn angle close to equinox meant the neutral torus was entirely eclipsed by Saturn around midnight. Therefore, with the neutral torus source in shadow, no photoelectrons can be produced to be transported into the shadow and observed by Cassini.

In summary:

- Saturn’s shadow geometry varies seasonally, modulating the total amount of neutral material in darkness.
- Photoelectron peaks are observed inside the shadow of Saturn, where local production is impossible.
- Saturn’s ionosphere is shadowed consistently throughout and is therefore ruled out as a source.
- Parts of the dense neutral torus remain sunlit and may act as a source with transport along magnetic field lines.
Chapter 5

Spacecraft Charging in Shadow

Dione, Rhea and Enceladus set against the dark side of Saturn. Image captured by Cassini in April 2011. Image credit: NASA/JPL-Caltech/SSI.

In this chapter, charged particle observations made in the shadows on Saturn, Rhea and Enceladus are presented. Observed sudden plasma density changes between sunlit and shadowed observations may be due to changes in spacecraft potential or real changes in plasma parameters. This study aims to qualitatively establish to what degree each of these factors contributes to the effect and discuss the evidence for real plasma density changes under shadow.
5.1 Introduction

The charging of a spacecraft is a product of the balance of the currents to/from the local plasma. The magnitude of these currents depend on the conditions in the local plasma as well as the properties of the spacecraft (see Section 2.5). The spacecraft is observed to charge to different potentials depending on its location in the magnetosphere. This is because plasma density and temperature vary throughout the magnetosphere. Beyond $\approx 5 R_S$ plasma density tends to fall (see Figure 5.1a). Both hot and cold electron temperature tend to rise throughout the inner magnetosphere until $\approx 10 R_S$ [Schippers et al., 2008].

Spacecraft potential (hereafter $\Phi_{SC}$) varies throughout the magnetosphere as the local plasma conditions change [Livi et al., 2014]. Figure 5.1b shows $\Phi_{SC}$ versus $R_S$. The potential is at its peak negative value when the plasma density is highest at $\approx 5 R_S$. After that, the general trend is that the spacecraft becomes less negatively charged with increasing L-shell and plasma density. $\Phi_{SC}$ starts to become positively charged at $\approx 12 R_S$, continuing the general trend towards more positively charged.

Key among the factors which contribute to $\Phi_{SC}$ are spacecraft photoelectrons produced by incident sunlight on the spacecraft. Generally, solar illumination is a constant contributor to charge balance and other local plasma changes are the dominant drivers behind changes in $\Phi_{SC}$. However, there are times where Cassini passes into the shadow of Saturn and the spacecraft moves from sunlight to darkness very quickly. These events give us the rare opportunity to study the effects of removing photoionisation on $\Phi_{SC}$. For more information on these shadow events, see the introduction sections of Chapter 4.

As discussed in Section 4.3.1, one of the typical features seen during all shadow events is an apparent electron density drop coinciding with the shadow boundary crossing. When the spacecraft exits the shadow back into sunlight the density typically recovers to approximately pre-shadow levels.
5.2. SATURN’S SHADOW CASE STUDIES

In this chapter, three events were chosen to study the effect of shadowing on $\Phi_{SC}$ (Table 5.1). They were chosen because they best satisfy the following selection criteria:

- Two clear boundaries between sunlight and the shadow of Saturn: an entry and exit.
- Electron and ion data available
- Minimal contamination from penetrating radiation

The key question this study seeks to answer is: are these apparent changes in density purely a result of changing $\Phi_{SC}$ due to loss of spacecraft photoionisation in the shadow? In order to answer this question, it is assumed that plasma either side of a shadow boundary has not changed significantly and the only difference between before and
Table 5.1: Summary of shadow events used to study the effect of shadowing on spacecraft potential $\Phi_{SC}$. In the event type column, the shadows encountered by the spacecraft on its trajectory are listed in order. S represents the shadow of Saturn, R the shadow of the rings and – represents gaps of direct sunlight between them. See Table B.1 for more information on these events.

<table>
<thead>
<tr>
<th>Case</th>
<th>Date</th>
<th>Event type</th>
<th>Trajectory direction</th>
<th>L-shell range</th>
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</thead>
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<td>R-S-R</td>
<td>Outbound</td>
<td>4.28 – 6.94</td>
</tr>
<tr>
<td>2</td>
<td>15\textsuperscript{th} July 2005</td>
<td>R-S-R</td>
<td>Outbound</td>
<td>4.41 – 7.11</td>
</tr>
<tr>
<td>3</td>
<td>17\textsuperscript{th} November 2007</td>
<td>S</td>
<td>Inbound</td>
<td>4.30 – 3.96</td>
</tr>
</tbody>
</table>

after the boundary is due to the changing potential of the spacecraft. The shadowed plasma spectrum is then potential shifted to account for a $\Phi_{SC}$ change and compared with the sunlit plasma spectrum. This is done to assess whether a potential shift is likely the cause and if so, how much the potential has changed.
5.2.1 Case Study 1: 3\textsuperscript{rd} May 2005

Figure 5.2: Summary plot showing Cassini data from the shadow event on 3\textsuperscript{rd} May 2005. Indicated along the top of the plots are the times when Cassini is being shadowed by Saturn’s rings and the body of Saturn. Each panel shares a common X axis of time in UT along the bottom. 

\begin{itemize}
  \item a) ELS electron energy spectrogram in DEF.
  \item b) IMS ion energy spectrogram in DEF. \textit{N.B.} Y axis energy scale is reversed (lowest energy at the top).
  \item c) Cassini distance from Saturn centre (in \( R_S \)) and spacecraft L-shell.
  \item d) Pitch angle in degrees of electrons measured by each ELS anode.
  \item e) ELS 3D moments, electron density (m\(^3\)).
  \item f) Magnetic field (nT) in Spacecraft coordinates.
\end{itemize}
The shadow event on 3rd May 2005 is one event in a series of orbits intersecting the shadow and represents a typical early mission event. The spacecraft enters the shadow of the rings, then the body of Saturn followed by the shadow of the rings again. Cassini encounters the shadow during the outbound leg of its orbit.

Figure 5.2 shows a summary of data from the CAPS and MAG instruments during the shadow event. These data are gathered before CAPS began regularly actuating and so there is none of the periodicity seen in some of the previous spectrograms. This however means that the pitch angle distribution is comparatively limited. The latter half of the ion spectrogram in Figure 5.2 displays the energy-banded ion structures first discovered by Thomsen et al. [2017], thought to be a result of interaction between the ions and field line resonance standing waves. The electron spectrogram displays a similar banded structure in the latter half of the plot decreasing in energy from ≈ 1000–100 eV. This structure is thought to be caused by a similar mechanism to the observed ion structure but for negative ions rather then positive.

**Estimating spacecraft potential**

In order to estimate the spacecraft, time averaged energy spectra either side of the shadow boundary are compared (see Figure 5.3). It is assumed that the difference between these spectra, observed ≈ 10 minutes apart, are caused primarily due to a shift in $\Phi_{\text{SC}}$. Figure 5.3b shows the spectra either side of a shadow boundary. In phase space density, $\Phi_{\text{SC}}$ results in a horizontal shifting of the spectra (see Figure 2.8). If our assumption holds, the energy difference (i.e. horizontal shift) between these spectra gives us the spacecraft potential change between each observation.

To measure this horizontal shift, a parameter grid search method is used and the potential returning the best $R^2$ correlation coefficient is selected as our best fit potential estimate. The error on each of these estimates is made using a full width, 90% maximum (See Figure 5.4). Using a full width, half maximum approach would result in unrealistically large errors (10+ volts) as the peak is very broad. The broad peak may indicate the assumption that the differences are wholly due to $\Phi_{\text{SC}}$ change may not be entirely valid, this is discussed further in the conclusions. This method is used through-
5.2. SATURN’S SHADOW CASE STUDIES

Figure 5.3: Ion data surrounding the spacecraft entry into shadow. a) IMS ion energy spectrogram in PSD. b) Time averaged energy spectra at times \( t_L \) and \( t_D \) indicated on the panel above), while in sunlight and in darkness respectively. The shadow boundary is indicated by the vertical dotted white line.

out this chapter for making \( \Phi_{SC} \) change estimates for a number of case studies.

Shadow entry

The ion data from Figure 5.5a panel b is used to estimate the change in \( \Phi_{SC} \) across this boundary. Using the method described earlier, the potential shift between the spectra from inside the shadow (\( t_D \) in green) and outside the shadow (\( t_L \) in blue) is estimated to be \(-1.8^{+1.0}_{-1.2} \) eV.

Figure 5.5a panel c shows that the shifted spectra (red) fits well onto the sunlit spectra (blue) over a larger energy range for ion data. Figure 5.5b panels b and c suggest a reasonable agreement in electron data for shifting by the value obtained using ion data. The already negatively charged spacecraft appears to become more negatively charged when entering shadow.
**Figure 5.4:** $R^2$ correlation coefficient for spacecraft potential shifting between the sunlit and shadowed spectra in Figure 5.4. The black dashed line indicated the maximum $R^2$. The red dashed lines indicate the 90% maximum errors.

**Shadow exit**

The same technique is used in reverse to come to an estimate of $+2.1^{+1.1}_{-1.3}$ eV shift between sunlight and shadowed spectra.

One notable difference is that in Figure 5.5b panel c it can be seen that the electron spectra deviates significantly at energies between $\approx 15$–200 eV. This does not appear to be an offset which can be entirely compensated for with the horizontal energy shifting of a potential change. The spacecraft charge becomes more positive on leaving the shadow but remains negative overall.
(a) Ion data surrounding the spacecraft entry into shadow. a) IMS ion energy spectrogram in PSD. b) Time averaged energy spectra at times $t_L$ and $t_D$ indicated on the panel above), while in sunlight and in darkness respectively. The shadow boundary is indicated by the vertical dotted white line. Also shown is the energy spectra from inside the shadow (time $t_D$), potential shifted to best match the energy spectra from outside the shadow (time $t_L$). c). Same as Panel b showing an extended logarithmic energy scale.

(b) Electron data surrounding the spacecraft entry into shadow. a) ELS electron energy spectrogram in PSD. b) Time averaged energy spectra at times $t_L$ and $t_D$ indicated on the panel above), while in sunlight and in darkness respectively. The shadow boundary is indicated by the vertical dotted white line. Also shown is the energy spectra from inside the shadow (time $t_D$), potential shifted to best match the energy spectra from outside the shadow (time $t_L$). c). Same as Panel b showing an extended logarithmic energy scale.

Figure 5.5: Spacecraft potential change estimation using ion and electron data across the shadow entry boundary on 3rd May 2005.
(a) Ion data surrounding the spacecraft exit from shadow. a) IMS ion energy spectrogram in PSD. b) Time averaged energy spectra at times $t_D$ and $t_L$ indicated on the panel above), while in darkness and in sunlight respectively. The shadow boundary is indicated by the vertical dotted white line. Also shown is the energy spectra from inside the shadow (time $t_D$), potential shifted to best match the energy spectra from outside the shadow (time $t_L$). c). Same as Panel b showing an extended logarithmic energy scale.

(b) Electron data surrounding the spacecraft exit from shadow. a) ELS electron energy spectrogram in PSD. b) Time averaged energy spectra at times $t_D$ and $t_L$ indicated on the panel above), while in darkness and in sunlight respectively. The shadow boundary is indicated by the vertical dotted white line. Also shown is the energy spectra from inside the shadow (time $t_D$), potential shifted to best match the energy spectra from outside the shadow (time $t_L$). c). Same as Panel b showing an extended logarithmic energy scale.

**Figure 5.6:** Spacecraft potential change estimation using ion and electron data across the shadow exit boundary on 3rd May 2005.
5.2. SATURN’S SHADOW CASE STUDIES

5.2.2 Case Study 2: 15th July 2005

Figure 5.7: Summary plot showing Cassini data from the shadow event on 15th July 2005. Indicated along the top of the plots are the times when Cassini is being shadowed by Saturn’s rings and the body of Saturn. Each panel shares a common X axis of time in UT along the bottom. a) ELS electron energy spectrogram in DEF. b) IMS ion energy spectrogram in DEF. N.B. Y axis energy scale is reversed (lowest energy at the top). c) Cassini distance from Saturn centre (in RS) and spacecraft L-shell. d) Pitch angle in degrees of electrons measured by each ELS anode. e) ELS 3D moments, electron density (m³). f) Magnetic field (nT) in Spacecraft coordinates.
The shadow event on 15\textsuperscript{th} July 2005 is another event in the same early mission shadow event series as case 1. The spacecraft follows the same structure as Case 1, entering the shadow of the rings, then the body of Saturn followed by the shadow of the rings again. Cassini encounters the shadow during the outbound leg of its orbit.

Figure 5.7 shows a summary of data from the CAPS and MAG instruments during the shadow event. These data are gathered before CAPS began regularly actuating and so there is none of the periodicity seen in some of the previous spectrograms. The electron spectrogram in Figure 5.7b appears to show a similar energy-banded structure in the latter half of the plot decreasing in energy over $\approx 1000$–$100$ eV. Interestingly, no energy-banded structures are seen in the ion spectrogram. It is currently unclear why this might be the case.

**Shadow entry**

The ion data from Figure 5.8a panel b is used to estimate the change in $\Phi_{SC}$ across this boundary. Using the method described earlier, the potential shift between the spectra from inside the shadow ($t_D$ in green) and outside the shadow ($t_L$ in blue) is estimated to be $-1.0^{+0.8}_{-0.9}$ eV.

Ion spectra in Figure 5.8a panel c shows that the shifted spectra (red) fits well onto the sunlit spectra (blue) over a larger energy range. Notably, the shifted electron data in Figure 5.8b (red) does not match well with the observed sunlit spectra (blue). This suggests the potential estimate made using the ion data does not fully explain the data surrounding the boundary. It appears likely the electron density has also decreased between the observation in sunlight and the one in shadow.

**Shadow exit**

The same technique is used in reverse to come to an estimate of $+2.4^{+0.7}_{-0.9}$ eV shift between sunlight and shadowed spectra.
5.2. SATURN’S SHADOW CASE STUDIES

(a) Ion data surrounding the spacecraft entry into shadow. a) IMS ion energy spectrogram in PSD. b) Time averaged energy spectra at times $t_L$ and $t_D$ indicated on the panel above), while in sunlight and in darkness respectively. The shadow boundary is indicated by the vertical dotted white line. Also shown is the energy spectra from inside the shadow (time $t_D$), potential shifted to best match the energy spectra from outside the shadow (time $t_L$). c). Same as Panel b showing an extended logarithmic energy scale.

(b) Electron data surrounding the spacecraft entry into shadow. a) ELS electron energy spectrogram in PSD. b) Time averaged energy spectra at times $t_L$ and $t_D$ indicated on the panel above), while in sunlight and in darkness respectively. The shadow boundary is indicated by the vertical dotted white line. Also shown is the energy spectra from inside the shadow (time $t_D$), potential shifted to best match the energy spectra from outside the shadow (time $t_L$). c). Same as Panel b showing an extended logarithmic energy scale.

Figure 5.8: Spacecraft potential change estimation using electron and ion data across the shadow entry boundary on 15th July 2005.
(a) Ion data surrounding the spacecraft exit from shadow. a) IMS ion energy spectrogram in PSD. b) Time averaged energy spectra at times $t_D$ and $t_L$ indicated on the panel above), while in darkness and in sunlight respectively. The shadow boundary is indicated by the vertical dotted white line. Also shown is the energy spectra from inside the shadow (time $t_D$), potential shifted to best match the energy spectra from outside the shadow (time $t_L$). c). Same as Panel b showing an extended logarithmic energy scale.

(b) Electron data surrounding the spacecraft exit from shadow. a) ELS electron energy spectrogram in PSD. b) Time averaged energy spectra at times $t_D$ and $t_L$ indicated on the panel above), while in darkness and in sunlight respectively. The shadow boundary is indicated by the vertical dotted white line. Also shown is the energy spectra from inside the shadow (time $t_D$), potential shifted to best match the energy spectra from outside the shadow (time $t_L$). c). Same as Panel b showing an extended logarithmic energy scale.

Figure 5.9: Spacecraft potential change estimation using electron and ion data across the shadow exit boundary on 15th July 2005.
5.2.3 Case Study 3: 17th November 2007

![Figure 5.10](image)

**Figure 5.10:** Summary plot showing Cassini data from the shadow event on 17th November 2007. Indicated along the top of the plots are the times when Cassini is being shadowed by Saturn’s rings and the body of Saturn. Each panel shares a common X axis of time in UT along the bottom.  

- **a)** ELS electron energy spectrogram in DEF.  
- **b)** IMS ion energy spectrogram in DEF. *N.B.* Y axis energy scale is reversed (lowest energy at the top).  
- **c)** Cassini distance from Saturn centre (in Rs) and spacecraft L-shell.  
- **d)** Pitch angle in degrees of electrons measured by each ELS anode.  
- **e)** ELS 3D moments, electron density (m³).  
- **f)** Magnetic field (nT) in Spacecraft coordinates.
The shadow event on 17th November 2007 is one in a series of similar shadow events occurring in late 2007. The spacecraft encounters only the shadow of Saturn itself. Cassini encounters the shadow during the inbound leg of its orbit.

Figure 5.10 shows a summary of data from the CAPS and MAG instruments during the shadow event. The periodicity seen in both the electron and ion spectrograms are due to the actuation of the CAPS instrument and the analysis is made somewhat more complicated as a result.

**Shadow entry**

Due to the instrument actuation, the ion data are harder to analyse than with the previous cases. For this reason, instead of using ion data, the electron data from Figure 5.11a panel b is used to estimate the change in $\Phi_{SC}$ across this boundary. Using the method described earlier, the potential shift between the spectra from inside the shadow ($t_D$ in green) and outside the shadow ($t_L$ in blue) is estimated to be $-1.0^{+0.8}_{-0.7}$ eV.

Figure 5.11b shows that applying the potential made using electron data does not explain the ion data well. In fact, contrary to the electron data, the ion data seems to suggest a positive potential change on shadow entry. It is unclear what may cause the spacecraft to become more positive on entering shadow, so it is likely due to real changes in the plasma.
5.2. SATURN’S SHADOW CASE STUDIES

Shadow exit

The same technique is used in reverse to come to an estimate of $+0.1^{+0.4}_{-0.5}$ eV shift between sunlight and shadowed spectra.

While the ion data for the exit boundary (Figure 5.11b) does not suggest a contradictory charging as above, the magnitude of the shift clearly does not fit well. The ion data for both the entry and exit boundaries of this event suggest a more complicated picture than a simple $\Phi_\text{SC}$ shift.
(a) Electron data surrounding the spacecraft entry into shadow. **a** ELS electron energy spectrogram in PSD. **b** Time averaged energy spectra at times $t_L$ and $t_D$ indicated on the panel above), while in sunlight and in darkness respectively. The shadow boundary is indicated by the vertical dotted white line. Also shown is the energy spectra from inside the shadow (time $t_D$), potential shifted to best match the energy spectra from outside the shadow (time $t_L$). **c**. Same as Panel b showing an extended logarithmic energy scale.

(b) Ion data surrounding the spacecraft entry into shadow. **a** IMS ion energy spectrogram in PSD. **b** Time averaged energy spectra at times $t_L$ and $t_D$ indicated on the panel above), while in sunlight and in darkness respectively. The shadow boundary is indicated by the vertical dotted white line. Also shown is the energy spectra from inside the shadow (time $t_D$), potential shifted to best match the energy spectra from outside the shadow (time $t_L$). **c**. Same as Panel b showing an extended logarithmic energy scale.

**Figure 5.11:** Spacecraft potential change estimation using electron and ion data across the shadow entry boundary on 17th November 2007.
(a) Electron data surrounding the spacecraft exit from shadow. **a)** ELS electron energy spectrogram in PSD. **b)** Time averaged energy spectra at times $t_D$ and $t_L$ indicated on the panel above, while in darkness and in sunlight respectively. The shadow boundary is indicated by the vertical dotted white line. Also shown is the energy spectra from inside the shadow (time $t_D$), potential shifted to best match the energy spectra from outside the shadow (time $t_L$). **c)** Same as Panel b showing an extended logarithmic energy scale.

(b) Ion data surrounding the spacecraft exit from shadow. **a)** IMS ion energy spectrogram in PSD. **b)** Time averaged energy spectra at times $t_D$ and $t_L$ indicated on the panel above, while in darkness and in sunlight respectively. The shadow boundary is indicated by the vertical dotted white line. Also shown is the energy spectra from inside the shadow (time $t_D$), potential shifted to best match the energy spectra from outside the shadow (time $t_L$). **c)** Same as Panel b showing an extended logarithmic energy scale.

**Figure 5.12:** Spacecraft potential change estimation using electron and ion data across the shadow exit boundary on 17\textsuperscript{th} November 2007.
5.3 Moon Shadow Case Studies

Along with the events where the spacecraft passed through the shadow of Saturn and the rings, Cassini also entered the shadow of several of Saturn’s inner moons during targeted flybys (see Table B.2). These shadow events are naturally much shorter time intervals than those shown in previous sections. The two flybys selected as case studies for this chapter are shown in Table 5.2.

In addition to during flybys of Saturn’s inner moons, Cassini also entered shadow a number of times during Titan flybys in the outer magnetosphere. 12 of these events are recorded in the supplemental material of Wellbrock et al. [2013], which recorded the observations of negative ions in Titan’s ionosphere. These events are not considered likely to be as suitable for analysing the effect of shadow on the spacecraft due to the comparatively low plasma density and complex environment close to Titan.

Table 5.2: Summary of moon shadow events used to study the effect of shadowing on spacecraft potential $\Phi_{SC}$.

<table>
<thead>
<tr>
<th>Case</th>
<th>Date</th>
<th>Flyby</th>
<th>L-shell range</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>11&lt;sup&gt;th&lt;/sup&gt; January 2011</td>
<td>Rhea R3</td>
<td>8.63 – 8.79</td>
</tr>
<tr>
<td>5</td>
<td>14&lt;sup&gt;th&lt;/sup&gt; April 2012</td>
<td>Enceladus E18</td>
<td>3.99 – 3.96</td>
</tr>
</tbody>
</table>

These moon shadows are naturally much smaller than the shadows of Saturn and the rings and the shadow passage events typically last only a few minutes. Despite this, they display similar characteristics to the Saturn and ring shadow events. Typically the electron density drops when the spacecraft enters the shadow followed by a recovery on exit.

In this section, the same assumptions are made as before to attempt to measure the $\Phi_{SC}$ change and assess how well a simple $\Phi_{SC}$ shift explains the observations.
5.3.1 Case Study 4: 11th January 2011 (Rhea Flyby R3)

Figure 5.13: Summary plot showing Cassini data from the shadow event on 11th January 2011. Indicated along the top of the plots are the times when Cassini is being shadowed by Saturn’s rings and the body of Saturn. Each panel shares a common X axis of time in UT along the bottom. 

- **a)** ELS electron energy spectrogram in DEF.
- **b)** IMS ion energy spectrogram in DEF. N.B. Y axis energy scale is reversed (lowest energy at the top).
- **c)** Cassini distance from Saturn centre (in $R_S$) and spacecraft L-shell.
- **d)** Pitch angle in degrees of electrons measured by each ELS anode.
- **e)** ELS 3D moments, electron density ($m^3$).
- **f)** Magnetic field (nT) in Spacecraft coordinates.
Cassini encountered the shadow of Rhea during the R3 flyby on 11\textsuperscript{th} January 2011. Figure 5.13 shows a summary of data from the CAPS and MAG instruments during the shadow event. Panel a shows the electron spectrogram for this shadow event. As with all shadow encounters, the electron density appears to drop for the duration of the shadow passage. Towards the end of the conventional shadow is a further electron density drop, more prominent at higher energies. This is due to what is referred to as the ‘energetic particle shadow’, where the moon itself is blocking and absorbing bouncing energetic particles. It is a common effect seen during moon flybys and is described in more detail for Enceladus in Section 1.4.2.

**Shadow entry**

The electron data from Figure 5.14a panel b is used to estimate the change in $\Phi_{SC}$ across this boundary. Using the method described earlier, the potential shift between the spectra from inside the shadow ($t_D$ in green) and outside the shadow ($t_L$ in blue) is estimated to be $-3.5^{+0.6}_{-1.0}$ eV.

Figure 5.14a panel c shows that the shifted spectra (red) fits well onto the sunlit spectra (blue) over a larger energy range for electron data. The ion data in Figure 5.14b however presents a much messier picture. It appears the shifted spectra (red) has been shifted in the wrong direction, which would suggest the spacecraft has become more positively charged (rather than negatively, as suggested by the electron data). It is considered likely that in addition to the spacecraft becoming more negatively charged in shadow, there may be significant plasma changes in this region.

**Shadow exit**

The same technique is used in reverse to come to an estimate of $+4.5^{+1.0}_{-1.3}$ eV shift between sunlight and shadowed spectra.

Figure 5.15a panels b and c suggest the spacecraft potential fitting is not good for the electron data. There is clearly a difference in electron density which cannot be reconciled with potential shifting alone. Figure 5.15b panels b and c present a messy picture from which little can be inferred.
5.3. MOON SHADOW CASE STUDIES

(a) Electron data surrounding the spacecraft entry into shadow. a) ELS electron energy spectrogram in PSD. b) Time averaged energy spectra at times $t_L$ and $t_D$ indicated on the panel above), while in sunlight and in darkness respectively. The shadow boundary is indicated by the vertical dotted white line. Also shown is the energy spectra from inside the shadow (time $t_D$), potential shifted to best match the energy spectra from outside the shadow (time $t_L$). c). Same as Panel b showing an extended logarithmic energy scale.

(b) Ion data surrounding the spacecraft entry into shadow. a) IMS ion energy spectrogram in PSD. b) Time averaged energy spectra at times $t_L$ and $t_D$ indicated on the panel above), while in sunlight and in darkness respectively. The shadow boundary is indicated by the vertical dotted white line. Also shown is the energy spectra from inside the shadow (time $t_D$), potential shifted to best match the energy spectra from outside the shadow (time $t_L$). c). Same as Panel b showing an extended logarithmic energy scale.

Figure 5.14: Spacecraft potential change estimation using electron and ion data across the shadow entry boundary on 11th January 2011.
(a) Electron data surrounding the spacecraft exit from shadow. a) ELS electron energy spectrogram in PSD. b) Time averaged energy spectra at times $t_D$ and $t_L$, indicated on the panel above), while in darkness and in sunlight respectively. The shadow boundary is indicated by the vertical dotted white line. Also shown is the energy spectra from inside the shadow (time $t_D$), potential shifted to best match the energy spectra from outside the shadow (time $t_L$). c). Same as Panel b showing an extended logarithmic energy scale.

(b) Ion data surrounding the spacecraft exit from shadow. a) IMS ion energy spectrogram in PSD. b) Time averaged energy spectra at times $t_D$ and $t_L$, indicated on the panel above), while in darkness and in sunlight respectively. The shadow boundary is indicated by the vertical dotted white line. Also shown is the energy spectra from inside the shadow (time $t_D$), potential shifted to best match the energy spectra from outside the shadow (time $t_L$). c). Same as Panel b showing an extended logarithmic energy scale.

**Figure 5.15:** Spacecraft potential change estimation using electron and ion data across the shadow exit boundary on 11th January 2011.
5.3.2 Case Study 5: 14\textsuperscript{th} April 2012 (Enceladus flyby E18)

![Summary plot showing Cassini data from the shadow event on 14\textsuperscript{th} April 2012. Indicated along the top of the plots are the times when Cassini is being shadowed by Saturn’s rings and the body of Saturn. Each panel shares a common X axis of time in UT along the bottom. a) ELS electron energy spectrogram in DEF. b) IMS ion energy spectrogram in DEF. N.B. Y axis energy scale is reversed (lowest energy at the top). c) Cassini distance from Saturn centre (in $R_S$) and spacecraft L-shell. d) Pitch angle in degrees of electrons measured by each ELS anode. e) ELS 3D moments, electron density (m$^{-3}$). f) Magnetic field (nT) in Spacecraft coordinates.](image)
Cassini encountered the shadow of Enceladus during the E18 flyby on 14th April 2012. The flyby is classed as a southern plume crossing encounter and followed a similar trajectory to that of E19 shown in Figure 3.1.

Figure 5.16 shows a summary of data from the CAPS and MAG instruments during the shadow event. As with all shadow encounters, the electron density appears to drop for the duration of the shadow passage. Panel a shows the electron spectrogram for this shadow event. Just after the conventional shadow is the energetic particle shadow of Enceladus. In this interval, the apparent missing data are in fact where the flux exceeds the colour scale chosen to better show the effect of the shadow on low energy electron populations. During this flyby, CAPS was oriented towards the direction of the spacecraft’s trajectory and so the high flux areas are caused by dust and negative ions entering the instrument [Jones et al., 2009; Coates et al., 2010].

**Shadow entry**

The electron data from Figure 5.17a panel b is used to estimate the change in $\Phi_{SC}$ across this boundary. Using the method described earlier, the potential shift between the spectra from inside the shadow ($t_D$ in green) and outside the shadow ($t_L$ in blue) is estimated to be $-0.3^{+0.4}_{-0.2}$ eV.

Figure 5.17a panel c shows that the shifted spectra (red) fits well onto the sunlit spectra (blue) over a larger energy range for electron data. Figure 5.17b suggests that the potential shift estimated using the electron data is not sufficient to explain the ion data. Again, it is considered likely that there may be significant plasma changes in this region, especially due to the presence of the Enceladus plume.
5.3. MOON SHADOW CASE STUDIES

Shadow exit

The same technique is used in reverse to come to an estimate of $-0.6^{+0.4}_{-0.4}$ eV shift between sunlight and shadowed spectra.

Figure 5.18a panels b and c suggest the spacecraft potential fitting is again not good for the electron data. This may be due to the presence of the Enceladus plume (seen as a density dropout in panel a) so close to the observations. The same applies for the ion data in Figure 5.18b panels b and c. There are clearly plasma density changes in both the electron and ion spectra which cannot be explained by potential shifting alone.
(a) Electron data surrounding the spacecraft entry into shadow. **a)** ELS electron energy spectrogram in PSD. **b)** Time averaged energy spectra at times $t_L$ and $t_D$ indicated on the panel above), while in sunlight and in darkness respectively. The shadow boundary is indicated by the vertical dotted white line. Also shown is the energy spectra from inside the shadow (time $t_D$), potential shifted to best match the energy spectra from outside the shadow (time $t_L$). **c)** Same as Panel **b** showing an extended logarithmic energy scale.

(b) Ion data surrounding the spacecraft entry into shadow. **a)** IMS ion energy spectrogram in PSD. **b)** Time averaged energy spectra at times $t_L$ and $t_D$ indicated on the panel above), while in sunlight and in darkness respectively. The shadow boundary is indicated by the vertical dotted white line. Also shown is the energy spectra from inside the shadow (time $t_D$), potential shifted to best match the energy spectra from outside the shadow (time $t_L$). **c)** Same as Panel **b** showing an extended logarithmic energy scale.

**Figure 5.17:** Spacecraft potential change estimation using electron and ion data across the shadow entry boundary on 14th April 2012.
5.3. MOON SHADOW CASE STUDIES

(a) Electron data surrounding the spacecraft exit from shadow. a) ELS electron energy spectrogram in PSD. b) Time averaged energy spectra at times $t_D$ and $t_L$ indicated on the panel above), while in darkness and in sunlight respectively. The shadow boundary is indicated by the vertical dotted white line. Also shown is the energy spectra from inside the shadow (time $t_D$), potential shifted to best match the energy spectra from outside the shadow (time $t_L$). c) Same as Panel b showing an extended logarithmic energy scale.

(b) Ion data surrounding the spacecraft exit from shadow. a) IMS ion energy spectrogram in PSD. b) Time averaged energy spectra at times $t_D$ and $t_L$ indicated on the panel above), while in darkness and in sunlight respectively. The shadow boundary is indicated by the vertical dotted white line. Also shown is the energy spectra from inside the shadow (time $t_D$), potential shifted to best match the energy spectra from outside the shadow (time $t_L$). c) Same as Panel b showing an extended logarithmic energy scale.

Figure 5.18: Spacecraft potential change estimation using electron and ion data across the shadow exit boundary on 14th April 2011.
5.4 Discussion and Analysis

5.4.1 Saturn Shadow Cases

The potential estimate results from Saturn shadow cases 1–3 are summarised in Table 5.3 along with the L-shell of the crossing and the electron temperature measured in sunlight just outside the boundary.

Table 5.3: Summary of potential change estimates for shadow events where the spacecraft passes through the shadow of Saturn (case studies 1–3).

<table>
<thead>
<tr>
<th>Case</th>
<th>Date</th>
<th>Shadow boundary</th>
<th>Potential change (V)</th>
<th>Electron temperature (eV)</th>
<th>L-shell</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3rd May 2005</td>
<td>entry</td>
<td>$-1.8^{+1.0}_{-1.2}$</td>
<td>29.9</td>
<td>5.06</td>
</tr>
<tr>
<td></td>
<td></td>
<td>exit</td>
<td>$+2.1^{+1.1}_{-1.3}$</td>
<td>26.2</td>
<td>6.23</td>
</tr>
<tr>
<td>2</td>
<td>15th July 2005</td>
<td>entry</td>
<td>$-1.0^{+0.8}_{-0.9}$</td>
<td>42.7</td>
<td>5.17</td>
</tr>
<tr>
<td></td>
<td></td>
<td>exit</td>
<td>$+2.4^{+0.7}_{-0.9}$</td>
<td>33.0</td>
<td>6.36</td>
</tr>
<tr>
<td>3</td>
<td>17th November 2007</td>
<td>entry</td>
<td>$-1.0^{+0.7}_{-0.7}$</td>
<td>18.2</td>
<td>4.29</td>
</tr>
<tr>
<td></td>
<td></td>
<td>exit</td>
<td>$+0.1^{+0.4}_{-0.5}$</td>
<td>42.9</td>
<td>3.96</td>
</tr>
</tbody>
</table>

Figure 5.19: Spacecraft potential change estimates $|\Delta \Phi_{SC}|$ against electron temperature. Each event consists of a shadow entry (▲) and a shadow exit (▼), connected by a dashed line.
5.4. DISCUSSION AND ANALYSIS

Figure 5.19 shows the relationship between the estimated absolute $\Phi_{SC}$ change $|\Delta \Phi_{SC}|$ versus the 3D moment calculated electron temperature. The electron temperature is shown for the sunlit side of each boundary, as previously calculated moments cannot be trusted in the shadow due to the rapid spacecraft potential change. In cases 1 and 2 (3rd May 2005 and 15th July 2005), the electron temperature is larger when the spacecraft enters the shadow compared to when it re-enters sunlight, the opposite is true for case 3 (17th November 2007). In all cases, the difference between the $\Phi_{SC}$ either side of a shadow boundary decreases with increasing electron temperature for each event.

![Figure 5.20: Spacecraft potential change estimates $|\Delta \Phi_{SC}|$ against L-shell. Each event consists of a shadow entry (▲) and a shadow exit (▼), connected by a dashed line.](image)

Figure 5.20 shows the relationship between the estimated absolute $\Phi_{SC}$ change $|\Delta \Phi_{SC}|$ versus L-shell. Since L-shell and electron temperature are inversely proportional in this L-shell range (Figure 5.1), it is not surprising there as an inverse relationship compared to Figure 5.19.
The trends seen in Figures 5.19 and 5.20 are common among the shadow events analysed which are not presented here. It is proposed that these observed trends are due to an effect illustrated in Figure 5.21. First considering an outbound shadow event like the one on 15\textsuperscript{th} July 2005. Between $\approx 4–12 R_S$, as L-shell increases, electron density and temperature also tends to increase [Schippers \textit{et al.}, 2008]. Before encountering the shadow, the $\Phi_{SC}$ follows the expected trend of becoming less negative with increasing L-shell. When Cassini enters the shadow, the potential becomes more negative as the balance of charge is instantly changed by the removal of spacecraft photoionisation. The $\Phi_{SC}$ appears to continue changing while inside the shadow as a result of changing plasma conditions, although not at the same rate which might be expected in the absence of shadow. When the spacecraft exits the shadow, the $\Phi_{SC}$ recovers. The events described here suggest that shadow boundaries at higher L-shells (and higher electron temperatures) are associated with larger $\Phi_{SC}$ changes. This suggests that the electron density/temperature profile with L-shell may be different in shadow compared to in sunlight.

The $\Phi_{SC}$ change estimates made for these cases cannot be considered the entire picture. There is sufficient evidence to suggest that the plasma density inside the shadow has changed. Most notably, Figures 5.6b and 5.8b suggest that the electron density falls inside the shadow. When the local plasma moves into the shadow there is a sudden loss of sunlight as an ionisation source. Therefore, the ratio between ionisation and recombination falls leading to a lower plasma density and a higher neutral density.
5.4. DISCUSSION AND ANALYSIS

5.4.2 Moon Shadow Cases

The potential estimate results from moon shadow cases 4–5 are summarised in Table 5.3 along with the L-shell of the crossing.

Table 5.4: Summary of potential change estimates for shadow events where the spacecraft passes through the shadow of some of Saturn’s moons (case studies 4–5).

<table>
<thead>
<tr>
<th>Case</th>
<th>Date</th>
<th>Flyby</th>
<th>Shadow boundary</th>
<th>Potential change (V)</th>
<th>L-shell</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>11\textsuperscript{th} January 2011</td>
<td>Rhea R3</td>
<td>entry</td>
<td>$-3.5^{+0.6}_{-1.0}$</td>
<td>8.63</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>exit</td>
<td>$+4.5^{+1.0}_{-1.3}$</td>
<td>8.79</td>
</tr>
<tr>
<td>5</td>
<td>15\textsuperscript{th} April 2012</td>
<td>Enceladus E18</td>
<td>entry</td>
<td>$-0.3^{+0.4}_{-0.2}$</td>
<td>3.99</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>exit</td>
<td>$-0.6^{+0.4}_{-0.4}$</td>
<td>3.96</td>
</tr>
</tbody>
</table>

The moon shadow events are naturally much shorter than the Saturn shadow events. Other than the effects associated with the moon itself, the plasma conditions do not change much between before and after the shadow. The change in $\Phi_{SC}$ appears to be larger at Rhea compared to Enceladus which fits well with the trend seen among Saturn shadow cases (larger $\Phi_{SC}$ changes at higher L-shells).

With both of these cases, there is a significant amount of uncertainty surrounding the shadow exit because it occurs either inside or close to the energetic particle shadow. Despite this, there is a strong case to suggest a $\Phi_{SC}$ shift is not sufficient to fully describe the difference between pre-shadow and post-shadow plasma. It is likely that there is a component of plasma density changes, especially in the electron distributions (see Figure 5.14a, Figure 5.15a, Figure 5.17a and Figure 5.18a).
5.5 Conclusions and Summary

In this chapter, plasma observations inside and surrounding the shadows of Saturn, Rhea and Enceladus are presented and analysed. The impact the shadowing on spacecraft charging is quantitatively estimated and discussed. Observations suggest that crossing the shadow boundary has a significant and immediate impact on the spacecraft potential, \( \Phi_{SC} \). There is strong evidence that spacecraft potential changes cannot fully explain the observations alone and plasma density changes in the shadow must also be present.

During Saturn’s shadow events, (cases 1–3), a number of common trends are observed. Firstly, when the spacecraft enters shadow, the \( \Phi_{SC} \) quickly becomes more negative and when the spacecraft re-enters sunlight the \( \Phi_{SC} \) becomes more positive. Secondly, the magnitude of the \( \Phi_{SC} \) change across the shadow boundary increases with decreasing electron temperature (and increasing L-shell). The shadows events at Rhea and Enceladus (cases 4–5) also support this trend with much larger \( \Phi_{SC} \) variation seen at Rhea (\( \approx 8 R_S \)), compared with Enceladus (\( \approx 4 R_S \)).

The original hypothesis of this study was to investigate whether the observed plasma changes across the shadow boundaries could be explained with spacecraft potential effects. As such, the \( \Phi_{SC} \) change estimates in this chapter have been made under the assumption that \( \Phi_{SC} \) change is the only free parameter available when comparing the pre-shadow and post-shadow spectra. The analysis confirms that a large portion of the plasma density changes can be explained with spacecraft potential shifting.

However, there is clear evidence that there must be a component of real plasma density change to fully explain the observations. In electron data from the case 1 (3rd May 2005) exit boundary and case 2 (15th July 2005) entry boundary, density differences are observed which cannot be explained by spacecraft potential shifting alone. Ion data from both shadow boundaries in case 3 (17th November 2007) disagrees (even contradicts) with spacecraft potential estimates made using electron data, strongly suggesting plasma densities changes in addition to spacecraft potential. Moon cases 4 and 5 both
also suggest plasma density changes, although it is likely a combination of effects from plasma shadowing and moon proximity effects (e.g. Enceladus plume).

In addition to this evidence, the broad $R^2$ peaks in the correlation analysis (Figure 5.4) suggests that there are is a meaningful difference between the sunlit and shadowed spectra which is not considered (i.e. plasma density variation). If the two spectra differed simply by potential alone, they would map onto one another by a fixed horizontal offset and the peak would be narrow and centred on the spacecraft potential. The broad correlation peaks indicate that there are gradient differences between the spectra, which means not only a horizontal shift is present, but also the shape of the spectra has changed significantly. Despite this, the analysis suggests spacecraft potential shifting can account for the majority of the density changes and is still the dominant effect. Therefore, it seems likely that the estimates made using this analysis still give good indication of real spacecraft potential change.

To quantify all the changing plasma and spacecraft parameters, a more complex model with many more free parameters beyond the scope of this study would need to be considered. Unfortunately, there are no RPWS $\Phi_{SC}$ estimates with which to compare during any shadow events used in this chapter.

The observations of a change in the local plasma conditions inside the shadow itself should not come as a surprise. Photoionisation contributes to the total ionisation of the abundant neutrals and when this is removed the total ionisation/recombination ratio will fall. This should result in lower plasma densities and higher neutral densities inside the shadow. The lower plasma density also effects the $\Phi_{SC}$, along with the loss of spacecraft photoelectrons from the charging balance.

In summary:

- Fast spacecraft potential $\Phi_{SC}$ changes are observed across the sunlight-shadow boundaries of Saturn, Rhea and Enceladus.

- Spacecraft potential becomes more negative when entering shadow and returns
to the ‘expected’ spacecraft potential $\Phi_{SC}$ when exiting back into sunlight.

- The magnitude of the spacecraft potential change across the shadow boundary increases with decreasing ambient electron temperature.

- There is significant evidence that local plasma density quickly drops inside the shadow due to the loss of the photoionisation plasma source.
Chapter 6

Conclusions and Further Work

Image of Saturn’s rings taken by Cassini on 13th September 2017. One of the last images Cassini sent back to Earth. Image credit: NASA/JPL-Caltech/SSI.
6.1 Summary and Conclusions

A combination of data analysis and modelling techniques have been used in this thesis to investigate the influence of solar radiation as an ionisation source in Saturn’s inner magnetosphere. The data used in this study were primarily from the Cassini CAPS instrument complimented by data from other Cassini particle and fields instruments. Modelling and fitting techniques are used throughout to compare to and enhance the information gained from the data analysis.

In Chapter 3 CAPS-ELS electron data were used to study the low energy electron spectra in the Enceladus plume. It was found that the observed spectra can be adequately reproduced by a modelled photoelectron production spectrum, including the presence of two previously unidentified peaks. The characteristic energy of photoelectron peaks also allowed this method to support spacecraft potential estimates made by the RPWS instrument. The study further extends the work of Schippers et al. [2009] and Coates et al. [2013] by applying modelling techniques developed in Schippers et al. [2009] to the new photoelectron environment first reported in Coates et al. [2013].

In Chapter 4 photoelectron observations made by CAPS-ELS in the shadow of Saturn were presented. A composite model of Saturn’s shadow, Enceladus neutral torus and spacecraft trajectory was used to evaluate the possible sources and transport mechanisms for these photoelectrons. Analysis suggested that the most likely scenario is that photoelectrons are produced in the neutral torus and transported along field lines deep into the shadow.

In Chapter 5 CAPS-ELS electron and ion data across the shadow boundaries of Saturn, Rhea and Enceladus was used to study the effect of shadowing on spacecraft potential. It was found that the loss of spacecraft photoemission caused the spacecraft to become more negatively charged when eclipsed. Analysis also suggested that after accounting for spacecraft potential, an observed plasma density drop inside the shadow still remains.
Photoelectrons

A key theme throughout this thesis has been the study of magnetospheric photoelectrons. Photoelectrons have been used as investigative tools at Earth, Mars, Venus and throughout Saturn’s magnetosphere (Coates et al. [2011] and references within). This work demonstrates some of the uses of photoelectron analysis as a tool for diagnosing other properties of the magnetosphere.

The first takes advantage of the characteristic energies of photoelectron peaks depending on the neutral species they are produced from. In Chapter 3 the modelled photoelectron production spectrum was created using neutral species observations by the Cassini INMS instrument. The subsequent fitting of that modelled spectrum to the observed photoelectron spectrum supports the original neutral species observations.

Photoelectron spectra can also be used to determine spacecraft potential using this same characteristic energy peak feature. In Chapter 3 the modelled spectrum was energy shifted by spacecraft potential estimates made by RPWS. The resulting comparison with observations were used to determine the RPWS estimates adequate for the purposes of fitting the two spectra. In the absence of sufficient spacecraft potential estimates from other instruments, it is possible to use this energy shifting of photoelectron peaks to determine the spacecraft potential to the best degree of accuracy the electron instrument will allow.

The observation of photoelectrons at some location distant to where they were produced can be used as tracers of magnetic field lines. In Chapter 4, photoelectrons are clearly observed within the shadow of Saturn where they cannot be produced locally. Pitch angle distribution information was used to support the theory of a nearby source (the neutral torus) rather than a distant one (Saturn’s ionosphere).

Finally, the study of photoelectrons is important as they are a key component of the magnetospheric plasma. Along with the plasma generated by photoionisation, photoelectrons with energies larger than the ionisation potential may themselves go on to
ionise further via electron impact ionisation. This makes them an important part of any modelling which seeks to describe the plasma dynamics of the outer planet magnetospheres (e.g. [Fleshman et al., 2012; Ozak et al., 2012]).

**Magnetoospheric eclipsing**

Another theme visited in this thesis is the analysis of the effects of magnetoospheric eclipsing in Saturn’s inner magnetosphere. Modelling work in Chapter 4 illustrates the geometry of Saturn’s shadow in the inner magnetosphere.

Along with its utility in analysing photoelectron observations, modelling in Chapter 4 highlights the seasonal variability of shadow geometry. At equinox it is estimated that up to 10% of the neutral torus is completely in shadow and cannot be photoionised. At solstice, the entire torus is sunlit at all local times due to the angling of the shadow. This has implications for total ionisation in the inner magnetosphere as the proportion of total neutral material in sunlight varies annually.

This annual variation is caused by the 27° inclination of Saturn’s equatorial plane to its orbit. At Jupiter, volcanic eruptions from its moon Io forms a similar torus structure to Enceladus’ at Saturn, the main difference being that Io’s is primarily a plasma torus. However, Jupiter has only a 3° inclination and so it is not expected to experience a large seasonal variation in magnetoospheric eclipsing.

Neptune has a similar inclination to Saturn’s at 30° and it has been suggested its moon Triton may act as a source of neutrals in the magnetosphere [Richardson, 1993]. Uranus has an extreme inclination of 98° and is expected to exhibit magnetoospheric dynamics unlike those seen at any other planet in our solar system. It is expected that seasonal variations in magnetoospheric eclipsing may have an impact on the total photoionisation rates in both of these magnetospheres. It is currently only possible to speculate on the possible magnetospheres of exoplanets. If the conditions which are common in our own solar system (large orbit-equatorial inclination and magnetoospheric plasma sources) are common in exoplanetary systems, then it can be expected that similar magnetoospheric eclipsing may be important.
In Chapter 5 analysis of the spacecraft potential changes on shadow entry and exit revealed that there is likely a lower electrons density inside the shadow. It is thought this density drop is caused by the loss of photoionisation as an ionisation source. This shifts the ionisation/recombination balance resulting in less plasma and more neutrals inside the shadowed region.

**Spacecraft shadowing**

The last topic visited in this thesis concerns the effect of shadowing on spacecraft potential. The spacecraft potential depends on balance of currents, one of which being photoemission from the spacecraft (see Section 2.5). When the spacecraft is eclipsed by a planet/moon, this current is removed and the spacecraft potential quickly shifts to a new balance point.

In Chapter 5, the spacecraft potential change across sunlight-shadow boundaries of Saturn, Rhea and Enceladus is estimated. It was found that the spacecraft consistently became more negatively charged inside the shadow and that the amount that the spacecraft potential changed appeared to be partially dependent on the electron temperature surrounding the crossing. This supports the idea that the spacecraft potential changes rapidly across the boundary as the photoemission portion of the current balance is removed and restored.

The accurate estimation of spacecraft potential is important for correcting moments and measured particle distribution functions whenever there are real electron/ion populations whose energy is \( \lesssim 2-3 \) times the spacecraft potential. Adjustments must be made in accordance with Liouville’s theorem (see Section 2.5 and references therein).
6.2 Further Work

The results reached during the studies in this thesis have given rise to new questions to be addressed by future research.

Photoelectrons at Enceladus

Chapter 3 discussed the comparison of photoelectron production spectra with observations made by CAPS-ELS in the plume of Enceladus. Photoelectron spectra in the plume of Enceladus are made readily observable due to the blocking of penetrating radiation by the moon. This penetrating radiation makes the large scale study of photoelectron dynamics in the inner magnetosphere challenging (see Figure 3.2 for examples of the penetrating radiation surrounding Enceladus’ orbit). Unfortunately, it was found that existing methods of penetrating radiation removal for CAPS-ELS data were insufficient to study the underlying photoelectron spectra.

Efforts were made to improve on the standard technique by extending the unpublished work of Lewis, Fazakerley, and Arridge. They created response maps for the efficiency of penetrating radiation entering the instrument (Figure 6.1a) and real plasma being measured (Figure 6.1b). These differ because penetrating radiation passes straight through the walls of the instrument (but is partially blocked by the body of the spacecraft) and the measured plasma is partially obscured by other instruments/parts of the spacecraft in ELS’s field of view (compare with instrument FOV in Figure 2.6). These effects mean that both the penetrating radiation intensity and real measured plasma recorded by ELS varies over the actuation sweep. In order to decipher the real plasma contribution, some assumptions are made about plasma from the same pitch angle during a sweep (at different times and different anodes) being the same and the radiation contribution can be separated and removed.
6.2. FURTHER WORK

(a) CAPS-ELS penetrating radiation efficiency response map. (b) CAPS-ELS electron measurement efficiency response map.

Figure 6.1: Figure from a presentation by Lewis, Fazakerley, and Arridge.

While attempting to implement and improve upon this method (and others) it became clear that in addition to these two factors, the rotation of the spacecraft was also influencing the amount of penetrating radiation reaching the instrument. Analysing data from the MIMI G1 channel (thought to be a good indicator of penetrating radiation) indicated that the orientation of the spacecraft changes the amount of radiation received, suggesting that the penetrating radiation must have some directional bias to it. Further work is needed to establish whether this can be accounted for in a way which would allow the automatic removal/reduction of penetrating radiation contamination for the large amount of electron data gathered in Saturn’s inner magnetosphere.

From a more general perspective, the techniques used in this chapter could be used by any future planetary mission equipped with an electron spectrometer. Measuring photoelectron spectra with ELS at energies <20 eV are somewhat hampered by the relatively large bin sizes at those energies. This is particularly problematic when attempting to estimate spacecraft potential by comparing measured spectra to the synthetic spectra as the potential is often comparable to the difference between energy bins (a few eV). Having launched in 1997, the instruments onboard Cassini had been in operation for 20 years and were developed years before that. Since then, instrument technology has improved (e.g. Rosetta IES has 4%ΔE/E [Burch et al., 2007]) and future missions may be able to take advantage of even better energy resolution electron spectra.
**Magnetospheric and spacecraft eclipsing**

Chapter 4 and Chapter 5 deal with the modelling of Saturn’s shadow geometry and CAPS-ELS observations of plasma inside the shadow. Alongside the various modelling improvements which could potentially be made (mostly covered in Section 4.2.4.1), there are a number of scientific questions which remain unanswered.

Firstly, evidence for electron density drops inside the shadow suggested that the ionisation/recombination rate ratio drops as the photoionisation plasma source is removed. If this is indeed the case, it would be expected that the neutral density inside the shadow should increase. This may be detectable using INMS or RPWS if data are available at the correct times. How this change in the neutral/plasma density ratio affects the global inner magnetosphere is an open question for future study.

Shadow geometry modelling in Section 4.2 revealed the potential seasonal impact of the varying sun-equatorial plane angle ($\theta_{SS}$). Studies have shown that the seasonally varying illumination of the rings can change the plasma composition in the inner magnetosphere [Elrod et al., 2012, 2014]. It is possible that the seasonally varying illumination of the neutral torus may be contributing to some of the seasonal variations detected by Cassini over the course of the mission (e.g. convective electric field [Andriopoulou et al., 2014]).

Finally in Chapter 5 there are a number of clear extensions to the study which may improve results and answer some of the questions raised. A sophisticated charging model could give insight into the theoretical effect of shadowing on the spacecraft potential. This in turn may help to quantify the apparent plasma density drop in the shadow and estimate how significant these effects are to the system as a whole.
Appendix A

Projection of an Oblate Spheroid

Reproduced here is the derivation for the projection of an oblate spheroid as found in Weisstein [2002].

The Cartesian equation for an oblate spheroid is

\[ \frac{x^2 + y^2}{a^2} + \frac{z^2}{c^2} = 1 \]  
(A.1)

The ellipticity of an oblate spheroid is defined as

\[ \varepsilon \equiv \sqrt{\frac{a^2 + c^2}{a^2}} \]
(A.2)

\[ \varepsilon = 1 - \frac{c}{a} \]

To find the projection of an oblate spheroid onto a plane, such that the Z axis is towards the observed and the X axis is in the plane of the page. In polar coordinates, the equation for an oblate spheroid becomes

\[ r(\theta) = a \left[ 1 + \frac{2\varepsilon - \varepsilon^2}{(1 - \varepsilon^2)} \cos^2 \theta \right]^{-1/2} \]  
(A.3)

Define

\[ k \equiv \frac{2\varepsilon - \varepsilon^2}{(1 - \varepsilon)^2} \]  
(A.4)

\[ x \equiv \sin \theta \]  
(A.5)
Plug (A.4), (A.5) into (A.3)

\[ r(\theta) = a[1+k(1-x^2)]^{-1/2} \]
\[ = a(1+k-2kx^2)^{-1/2} \quad (A.6) \]

Rotate the spheroid by an angle \( B \) such that the new symmetry axes are \( x \equiv x', y' \) and \( z' \). The projected height of a point in the \( x = 0 \) plane on the \( Y \) axis is

\[ y = r(\theta) \cos(\theta - B) \]
\[ = r(\theta)(\cos \theta \cos B - \sin \theta \sin B) \quad (A.7) \]
\[ = r(\theta)(\sqrt{1-x^2} \cos B + x \sin B) \]

To find the highest point

\[ \frac{dy}{d\theta} = \frac{a \sin(B - \theta)}{(1+k \cos^2 \theta)^{1/2}} + ak \frac{\cos(B - \theta) \cos \theta \sin \theta}{(1+k \cos^2 \theta)^{3/2}} = 0 \quad (A.8) \]
\[ \tan(B - \theta)(1+k \cos^2 \theta) + k \cos \theta \sin \theta = 0 \quad (A.9) \]

Since

\[ \tan(B - \theta) = \frac{\tan B - \tan \theta}{1 + \tan B \tan \theta} \]
\[ = \frac{\tan B - \frac{\sin \theta}{\sqrt{1-\sin^2 \theta}}}{1 + \tan B \frac{\sin \theta}{\sqrt{1-\sin^2 \theta}}} \quad (A.10) \]
\[ = \frac{\sqrt{1-\sin^2 \theta} \tan B - \sin \theta}{\sqrt{1-\sin^2 \theta} + \tan B \sin \theta} \]

Plugging (A.10) into (A.9),

\[ \frac{\sqrt{1-x^2} \tan B - x}{\sqrt{1-x^2} + x \tan B} [1+k(1-x^2)] + kx \sqrt{1-x^2} = 0 \quad (A.11) \]

Can be rearranged and simplified to

\[ x^2 = \frac{\tan^2 B(1+k)^2}{1+(1+k)^2 \tan^2 B} \quad (A.12) \]
Combining (A.6) and (A.7) and plugging in (A.12)

\[
y = a \frac{\sqrt{1-x^2 \cos B + x \sin B}}{\sqrt{1+k+kx^2}} \\
= a \frac{\cos B + (1+k)\frac{\sin^2 B}{\cos B}}{\sqrt{(1+k)[1+(1-k)\tan^2 B]}} \\
= a \frac{\cos^2 B + (1+k)\sin^2 B}{\cos B \sqrt{(1+k)[1+(1+k)\tan^2 B]}} \tag{A.13}
\]

Re-express \( k \) in terms of \( a \) and \( c \) and plug in (A.2)

\[
k = \frac{(2-\varepsilon)\varepsilon}{(1-\varepsilon)} \\
= \frac{(1+\frac{c}{a})(1-\frac{c}{a})}{\left(\frac{c}{a}\right)^2} \\
= 1 - \left(\frac{c}{a}\right)^2 \\
= \left(\frac{a}{c}\right)^2 - 1 \tag{A.14}
\]

Therefore

\[
1 + k = \left(\frac{a}{c}\right)^2 \tag{A.15}
\]

Plug (A.14) and (A.15) into (A.13) to obtain the semi-minor axis of the projected oblate spheroid,

\[
c' = a \frac{\cos^2 B + \left(\frac{a}{c}\right)^2 \sin^2 B}{\cos B \sqrt{\left(\frac{a}{c}\right)^2 \left[1 + \left(\frac{a}{c}\right)^2 \tan^2 B\right]}} \\
= a \frac{\cos^2 B + \left(\frac{a}{c}\right)^2 \sin^2 B}{\frac{a}{c} \sqrt{\cos^2 B + \left(\frac{a}{c}\right)^2 \sin^2 B}} \\
= c \sqrt{\cos^2 B + \left(\frac{a}{c}\right)^2 \sin^2 B} \\
= \sqrt{c^2 \cos^2 B + a^2 \sin^2 B} \tag{A.16}
\]

Finally, using (A.2)

\[
c' = a \sqrt{(1-\varepsilon)^2 \cos^2 B + \sin^2 B} \tag{A.17}
\]
Appendix B

Cassini Shadow Encounters

Table B.1 shows the recorded events where Cassini crossed into Saturn or the rings’ shadow.

These shadow encounters were recorded using NASA’s Eyes on the Solar System software. The software contains trajectory information for many NASA (and other) spacecraft. The timing of each shadow crossing was estimated visually and confirmed with features in the data.

Due to the manual nature of the data collection, there is likely to be some error in the timings. This error is estimated to be on the order of 10 seconds. Although it may be greater for the ring shadow timings as the edges of the ring are less well defined and the shadow in fades in. For the purposes of the shadow timings, the optically denser A and B rings are treated as the boundary.
<table>
<thead>
<tr>
<th>Date</th>
<th>DOY</th>
<th>Ring shadow 1</th>
<th>Saturn shadow</th>
<th>Ring shadow 2</th>
<th>L-shell range</th>
<th>Pitch angle range</th>
</tr>
</thead>
<tbody>
<tr>
<td>03 May 2005</td>
<td>123</td>
<td>03:28:00 – 04:30:40</td>
<td>05:11:12 – 07:42:50</td>
<td>08:23:00 – 09:20:46</td>
<td>4.28 – 6.94</td>
<td>8 – 108</td>
</tr>
<tr>
<td>15 Sep 2006</td>
<td>258</td>
<td>08:44:45 – 23:06:46</td>
<td></td>
<td></td>
<td>37.8 – 38.8</td>
<td>1 – 180</td>
</tr>
<tr>
<td>Date</td>
<td>DOY</td>
<td>Ring shadow 1</td>
<td>Saturn shadow</td>
<td>Ring shadow 2</td>
<td>L-shell range</td>
<td>Pitch angle range</td>
</tr>
<tr>
<td>------------</td>
<td>-----</td>
<td>----------------------</td>
<td>---------------</td>
<td>----------------------</td>
<td>---------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>03 Dec 2007</td>
<td>337</td>
<td>04:58:50 – 06:10:05</td>
<td>06:10:05 – 07:32:50</td>
<td></td>
<td>3.45 – 2.55</td>
<td>0 – 175</td>
</tr>
<tr>
<td>Date</td>
<td>DOY</td>
<td>Ring shadow 1</td>
<td>Saturn shadow</td>
<td>Ring shadow 2</td>
<td>L-shell range</td>
<td>Pitch angle range</td>
</tr>
<tr>
<td>------------</td>
<td>-----</td>
<td>------------------------</td>
<td>---------------</td>
<td>------------------------</td>
<td>---------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>09 Jun 2008</td>
<td>161</td>
<td>01:12:52 – 02:03:44</td>
<td></td>
<td>2.96 – 2.76</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16 Jun 2008</td>
<td>168</td>
<td>04:20:04 – 05:09:35</td>
<td></td>
<td>2.93 – 2.75</td>
<td>1 – 144</td>
<td></td>
</tr>
<tr>
<td>30 Jun 2008</td>
<td>182</td>
<td>08:17:45 – 09:03:34</td>
<td></td>
<td>2.89 – 2.74</td>
<td>7 – 178</td>
<td></td>
</tr>
<tr>
<td>07 Jul 2008</td>
<td>189</td>
<td>09:07:43 – 09:51:30</td>
<td></td>
<td>2.87 – 2.73</td>
<td>1 – 122</td>
<td></td>
</tr>
<tr>
<td>Date</td>
<td>DOY</td>
<td>Ring shadow 1</td>
<td>Saturn shadow</td>
<td>Ring shadow 2</td>
<td>L-shell range</td>
<td>Pitch angle range</td>
</tr>
<tr>
<td>------------</td>
<td>-----</td>
<td>---------------------</td>
<td>--------------------</td>
<td>---------------------</td>
<td>---------------</td>
<td>------------------</td>
</tr>
<tr>
<td>10 Sep 2008</td>
<td>254</td>
<td>07:50:33 – 07:58:13</td>
<td></td>
<td>08:02:14 – 08:10:00</td>
<td>4.07 – 3.98</td>
<td>1 – 121</td>
</tr>
<tr>
<td>Date</td>
<td>DOY</td>
<td>Ring shadow 1</td>
<td>Saturn shadow</td>
<td>Ring shadow 2</td>
<td>L-shell range</td>
<td>Pitch angle range</td>
</tr>
<tr>
<td>------------</td>
<td>-----</td>
<td>--------------------------</td>
<td>---------------</td>
<td>---------------</td>
<td>---------------</td>
<td>------------------</td>
</tr>
<tr>
<td>13 Feb 2010</td>
<td>044</td>
<td>05:58:28 – 09:39:00</td>
<td>8.05 – 6.06</td>
<td>6 – 164</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20 Mar 2010</td>
<td>079</td>
<td>10:34:08 – 14:05:03</td>
<td>7.93 – 6.00</td>
<td>0 – 163</td>
<td></td>
<td></td>
</tr>
<tr>
<td>07 Apr 2010</td>
<td>097</td>
<td>00:56:06 – 04:14:55</td>
<td>8.43 – 6.74</td>
<td>1 – 180</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Date</td>
<td>DOY</td>
<td>Ring shadow 1</td>
<td>Saturn shadow</td>
<td>Ring shadow 2</td>
<td>L-shell range</td>
<td>Pitch angle range</td>
</tr>
<tr>
<td>------------</td>
<td>-----</td>
<td>---------------------</td>
<td>---------------</td>
<td>---------------</td>
<td>---------------</td>
<td>------------------</td>
</tr>
<tr>
<td>19 Jun 2010</td>
<td>170</td>
<td>00:17:00 – 03:10:11</td>
<td>5.82 – 4.10</td>
<td>3 – 171</td>
<td></td>
<td></td>
</tr>
<tr>
<td>02 Sep 2010</td>
<td>245</td>
<td>14:36:04 – 18:13:28</td>
<td>8.08 – 6.15</td>
<td>1 – 180</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table B.2: Table of events where Cassini crossed into the shadow of one of Saturn’s moons.

<table>
<thead>
<tr>
<th>Date</th>
<th>DOY</th>
<th>Flyby</th>
<th>Shadow</th>
<th>L-shell range</th>
<th>Pitch angle range</th>
</tr>
</thead>
<tbody>
<tr>
<td>11 Jan 2011</td>
<td>011</td>
<td>Rhea R3</td>
<td>04:44:12 – 04:52:45</td>
<td>8.63 – 8.79</td>
<td>0 – 133</td>
</tr>
</tbody>
</table>
Appendix C

Nomenclature

Acronyms

ASI Agenzia Spaziale Italiana
CA Closest Approach
CAPS Cassini Plasma Spectrometer
DEF Differential Energy Flux
DNF Differential Number Flux
ELS Electron Spectrometer
ESA European Space Agency
FOV Field-of-view
FPP Field and Particle Pallet
HGA High Gain Antenna
HST Hubble Space Telescope
IBS Ion Beam Spectrometer
IMF Interplanetary Magnetic Field
IMS Ion Mass Spectrometer
INMS Ion and Neutral Mass Spectrometer
ISS Imaging Science Subsystem
JPL Jet Propulsion Laboratory
LEMMS Low Energy Magnetospheric Measurement system
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>LT</td>
<td>Local Time</td>
</tr>
<tr>
<td>MCP</td>
<td>Microchannel Plate</td>
</tr>
<tr>
<td>MIMI</td>
<td>Magnetospheric Imaging Instrument</td>
</tr>
<tr>
<td>MHD</td>
<td>Magnetohydrodynamics</td>
</tr>
<tr>
<td>MPS</td>
<td>Max Planck Institute for Solar System Research</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>PSD</td>
<td>Phase Space Density</td>
</tr>
<tr>
<td>RPWS</td>
<td>Radio and Plasma Wave Science</td>
</tr>
<tr>
<td>RTG</td>
<td>Radioisotope Thermoelectric Generator</td>
</tr>
<tr>
<td>SSI</td>
<td>Space Science Institute</td>
</tr>
<tr>
<td>UVIS</td>
<td>Ultraviolet Imaging Spectrometer</td>
</tr>
<tr>
<td>UT</td>
<td>Universal Time</td>
</tr>
<tr>
<td>WSR</td>
<td>Wilcoxon Signed-Rank</td>
</tr>
</tbody>
</table>
### Constants

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_0$</td>
<td>Permittivity of free space</td>
<td>$8.8542 \times 10^{-12}$ m$^{-3}$ kg$^{-1}$ s$^4$ A$^2$</td>
</tr>
<tr>
<td>$\mu_0$</td>
<td>Permeability of free space</td>
<td>$1.2566 \times 10^{-6}$ m kg s$^{-2}$ A$^{-2}$</td>
</tr>
<tr>
<td>AU</td>
<td>Astronomical unit</td>
<td>$1.496 \times 10^8$ km</td>
</tr>
<tr>
<td>$e$</td>
<td>Electron charge</td>
<td>$1.6022 \times 10^{-19}$ C</td>
</tr>
<tr>
<td>$h$</td>
<td>Planck’s constant</td>
<td>$6.6261 \times 10^{-34}$ m$^2$ kg s$^{-1}$</td>
</tr>
<tr>
<td>$k_B$</td>
<td>Bolzmann constant</td>
<td>$1.3806 \times 10^{-23}$ m$^2$ kg s$^{-2}$ K$^{-1}$</td>
</tr>
<tr>
<td>$m_e$</td>
<td>Electron mass</td>
<td>$9.1094 \times 10^{-31}$ kg</td>
</tr>
<tr>
<td>$R_S = R_{\text{equatorial}}$</td>
<td>Saturn radius (equatorial)</td>
<td>60268 km</td>
</tr>
<tr>
<td>$R_{\text{polar}}$</td>
<td>Saturn radius (polar)</td>
<td>54364 km</td>
</tr>
<tr>
<td>$R_{\text{En}}$</td>
<td>Enceladus radius</td>
<td>252 km</td>
</tr>
</tbody>
</table>
Symbols

\( \alpha \)  Pitch angle  
\( \varepsilon \)  Ellipticity  
\( \theta_{SS} \)  Angle between the Sun and Saturn’s equatorial plane  
\( \lambda_D \)  Debye length  
\( \Phi_D \)  Debye potential  
\( \Phi_{SC} \)  Spacecraft potential  
\( \varphi \)  Threshold ionisation energy
Bibliography


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