SATURN’S MAGNETOSPHERE: INFLUENCES, INTERACTIONS AND DYNAMICS

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I, Sheila Kanani, 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 thesis.

Signed ..............................................................
“Ishimasi! What are you doing?”
“I’m writing a book about Saturn, Ashton.”
“I know what Saturn is. It’s a far far away planet with lots of rings round it made of stuff and planet things.”

Ashton Jayanti Ferdinand, aged 3.5 years. He later decided his baby sister Naia was from Saturn or Jupiter and we’d “need a rocket ship to take her back”.


**ABSTRACT**

In this thesis we use data from the Cassini spacecraft in order to investigate the influences on Saturn’s magnetosphere, and the dynamics and interactions that occur within it. The primary instrument for this study is the Cassini electron spectrometer (CAPS-ELS), analysing low energy electron data to examine three areas of research, which are discussed and developed in this thesis.

The first study concerns the magnetopause of Saturn, the boundary between the region of space dominated by the planet’s magnetic field and the interplanetary magnetic field. We develop a new pressure balance model using a multi-instrument data analysis, building on past models and including new features. It has been shown that the model has improved on previous models due to the inclusion of the suprathermal plasma and variable static pressures in the pressure balance equation providing more realistic results. It is currently the most up to date model of Saturn’s magnetopause.

The second study concerns flux tube interchange and injection events in Saturn’s inner magnetosphere. A new survey of these features was carried out across the entire dataset in order to learn more about plasma circulation, and to answer questions such as whether injection events with increases in magnetic field strength are always found at the equator. By examining the electron and ion data, we test previous interpretations of some events, analyse other such events in detail, and demonstrate a method through which the radial plasma flow direction of interchanging flux tubes can be determined.

Pitch angle distributions, magnetic field data and plasma flow models were
considered in order to help establish plasma circulation patterns in the kronian magnetosphere. We were able to determine the flow direction of 17 events and use magnetic field data from 32 events to conclude that generally increases in magnetic field strength are indeed found at the equator. We believe our work has shown that Saturn exhibits general and isolated plasma flow, with the isolated plasma flow occurring as “bubbles” in the plasma.

The third study concerns low energy electron enhancements in the inner magnetosphere, specifically those associated with Saturn’s moon Enceladus. During an investigation of close flybys of Enceladus, discrete, short duration enhancements were found in the low energy electron plasma. We present the new features seen in the Enceladus L shell region of the kronian magnetosphere. The data from these new features were surveyed and some possible creation mechanisms are discussed. In total, over 600 spikes were found between $L = 3.5$ and $4.5$ from data between Saturn Orbit Insertion and June 2010, showing a preference about the equatorial region but no obvious patterns in local time. Some spikes appear to extend to dispersive higher energy signatures, which are generally associated with injection events and hence these types of spikes were investigated accordingly. Although one formation process was not found to account for all the events, we rule out several processes, such as spacecraft charging and thruster engine firing as causes for the spikes. We believe that our results show that different creation mechanisms can be responsible for different types of low energy electron enhancements.
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CHAPTER 1  INTRODUCTION

“I think I’m having a thought...I am! I’m having a thought!”

Xander, BTVS, episode 2.14

The study of planetary magnetospheres has been of particular interest since the dawn of space research. The studies began with that of the Earth, and then the first in situ observations of other magnetospheres took place when Pioneer 10 reached Jupiter in late 1973 and Mariner 10 reached Mercury a few months later in March 1974. Instruments have become increasingly advanced - magnetospheric physics is now a field of physics in its own right and our interest has naturally widened to include other planetary magnetospheres. Our knowledge of Saturn’s magnetosphere has increased dramatically since the beginning of the Cassini mission in 2004; the Cassini spacecraft is orbiting Saturn and transmitting data to us as this thesis is being written.

The scientific analysis in this thesis deals mainly with the influences on, and interactions and dynamics of, the kronian magnetosphere. The study of a planetary magnetosphere encompasses the space environment around the planet, the interaction between particles and fields, the influence of the Sun and solar wind and, where applicable, studies of the material originating inside the magnetosphere. It is therefore necessary to consider some basic concepts of space plasmas and electrodynamics before the analysis is described. Much of the introductory material presented in this chapter is sourced from textbooks.
Chapter 1: Introduction

such as Baumjohann and Treumann [1997], Kivelson and Russell [1995] and Cravens [2004], unless otherwise stated.

1.1 Space Plasma Physics

1.1.1 What is a plasma?

A plasma is a quasi neutral gas of charged particles which exhibits collective behaviour. Plasmas are thought of as the fourth state of matter. This is because they are in a gaseous state but sufficiently ionised such that equal numbers of negative and positive charge carriers, electrons and ions respectively, are ‘free’ to interact with and modify the electric and magnetic fields around them.

Plasmas are the most common state of matter; they can be found in a neon sign or lightning on Earth, in the Earth’s ionosphere, in our Sun and other stars and, as mentioned, are also contained within planetary magnetospheres. Almost all the visible matter in the Universe, by mass and volume, is plasma. This is a very important state of matter indeed.

Electric potentials are felt by charged particles and each charged particle will exert its own potential, via the Coulomb force, on surrounding particles. The electric potential in a vacuum is therefore known as the Coulomb potential and is defined by equation 1.1, where \( q \) is the charge of the particle, \( \varepsilon_0 \) is the permittivity of free space and \( r \) the distance between the charges.

\[
\phi_c = \frac{q}{4\pi\varepsilon_0 r}
\]

Because of the generally equal numbers of negative and positive charges, plasma maintains a net charge of zero. However, due to thermal fluctuations in
the plasma, it can only be thought of as quasi-neutral. In a quasi-neutral gas there may be transient net concentrations of particles of the same charge, so it is not truly neutral, but on average, on large scales and steady states, the gas is neutral. Charge concentrations come from particle motion, waves and oscillations. These are transient due to electrostatic repulsion which is always acting to reduce the concentration of like charges. Plasmas act to retain their quasi-neutrality, but only over smaller spatial scales, shorter than the Debye length – the distance over which charge carriers can suppress the Coulomb potential by a factor of $e$ – individual charges in a plasma can be distinguished. Plasmas can therefore only be considered quasi-neutral when their length scale, $L$, is much greater than the Debye length, $\lambda_D$.

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

The Debye length is defined in equation 1.2 where $k_B$ is Boltzmann’s constant, $T_e$ is the electron temperature, $n$ is the number density of electrons and $q_e$ is the charge on the electron. Electrons are considered rather than ions because they are more mobile and less massive.

If a charged particle is inserted into a plasma the neutrality of the plasma is affected. Charge carriers in the plasma shift to ‘shield’ the object so that neutrality is re-established. The shielding is a collective effect, requiring many electrons to move closer to the charged particle to weaken its long-range potential, as the Debye length is large compared to the inter-particle spacing.
The further an electron is from the charged particle the lower the effects of the electrostatic potential force, thus the smaller the change in the electron motion.

The net potential is the sum of the Coulomb potential (unshielded) of the particle plus the potential due to the local collection of electron charges. Beyond a few Debye lengths away from the ‘source charge’ there is in essence no disruption of the plasma.

The potential is dependent on the Debye length, which is controlled by the number density of shielding particles and their temperatures. The potential is thus referred to as the Debye potential, as in equation 1.3.

\[ \phi_D = \frac{q}{4\pi\varepsilon_0 r} e^{-\frac{r}{\lambda_D}} \]

The Debye length can also be thought of as the radius of the Debye sphere and for an ideal plasma, within the Debye sphere there has to be sufficient number of particles, such that the condition in equation 1.4 is met. This is called the collective behaviour condition.

\[ N_D = \frac{4}{3} \pi \lambda_D^3 n \gg 1 \]

where \( N_D \) is the Debye number, the number of particles in the Debye sphere.

In reacting to any perturbations within the quasi-neutrality of the plasma, the electrons, due to the fact they are more mobile and have less mass, move to reduce the charge density imbalance. The ions move slightly too, but the main charge variation is due to that of the electron motion. This movement results in
a natural oscillation frequency called the electron plasma frequency, and is given in equation 1.5

\[
\omega_{pe} = \sqrt{\frac{nq_e^2}{\varepsilon_0 m_e}}
\]

where \( m_e \) is the mass of an electron.

The electron plasma frequency should be large in comparison to the electron collision frequency in order for the plasma to be considered ‘collisionless’. If this condition is met, electrostatic interactions dominate over gas kinetic processes.

The distribution and motion of a plasma depends on local conditions and the state of remote regions of plasma. Charged particles that act in a collective manner can induce an electric field. The motion of charged particles may constitute an electric current and thus produce a magnetic field. When many particles are travelling together in an ordered way their combined current can generate stronger magnetic fields which can exert their force over a longer range. This ordered motion is another example of ‘collective behaviour’.

For collective behaviour to be achievable the plasma must be a gas with free charges. This means the main influence on the plasma is not from collisions as is the case in neutral gases but from the combined magnetic and electric fields of the constituent charged particles. A free charge is a particle with kinetic energy larger than its electrostatic potential energy (due to its nearest
neighbour). Such a particle can move without being strongly repelled or attracted by a neighbouring particle.

Space plasmas are typically collisionless due to the fact that the density is so low. Their charged particles rarely encounter each other in close enough proximity that their electrostatic attraction or repulsion becomes the dominant force on them. Collisions of charged particles with neutral atoms are more frequent, thus more important, in the ionosphere. Collisions are also relatively important in the magnetosphere of Saturn, more so than at other Solar System magnetospheres, because of the large amount of neutral material present [Smith et al., 2010].

How plasmas react to electromagnetic fields is complex because not only are there external fields, but there are also fields generated internally when the particles are in motion. There are three approaches when considering plasma dynamics, used separately depending on which is most relevant for the nature of the problem to be solved.

The first, single particle motion, is to consider individual particles and their effect on the electric and magnetic fields. Only external electromagnetic fields are considered and internal collective effects are ignored. This approach is useful when describing the motion of radiation belt charged particles, however even in a low density system there are too many particles for this to be a realistic option.

The second, kinetic theory, tries to overcome this problem by describing the plasma using a statistical approach. Kinetic theory explains the motion of plasma as a distribution function through space and time.
The final technique, \textit{magnetohydrodynamics (MHD)}, is to consider the plasma as a conducting fluid and examine how the interaction between this fluid and electric and magnetic fields, affects the equations of fluid dynamics.

1.1.2 Single particle motion

Individual particles behave differently when subjected to electric and magnetic fields respectively. Charged particles are also able to create and alter these fields.

To describe the generation of electric and magnetic fields and the forces felt by charged particles in such fields, Maxwell’s equations are used. Here they are stated in differential form.

\begin{equation}
\nabla E = \frac{\rho}{\varepsilon_0}
\end{equation}

Equation 1.6 is the first of Maxwell’s equations. It is known as Gauss’s Law, which defines the generation of the electric field by charges (also known as electrostatics). \(E\) is the vector electric field and \(\rho\) is the charge density. This equation shows that the divergence of the electric field equals the ratio between the charge density and the permittivity of free space.

The 2nd of Maxwell’s equations, equivalent to equation 1.6 but for the magnetic field, \(B\), is shown in equation 1.7. The divergence of \(B\) must equal zero, due to the fact that there are no magnetic monopoles. The magnetic flux into a volume is equal to the magnetic flux leaving it.
Maxwell’s 3rd equation, the Faraday equation (1.8) describes the generation of an induced electric field that occurs when a magnetic field is changing with time.

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

The final Maxwell’s equation is Ampère’s Law. Ampère’s Law describes the generation of the magnetic field by flowing electric current or when an electric field is changing with time. It is shown in equation 1.9 where \( j \) is the current density and \( \mu_0 \) is the permeability of free space.

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

Because \( \mu_0 \varepsilon_0 = c^{-2} \), the second term in Ampère’s Law is usually considered negligible because most Solar System plasmas are non-relativistic, except when considering electromagnetic wave propagation.

In order to solve the equations of motion, individual particle interactions are not considered and only the effects of motion due to externally imposed fields are taken into account. The Lorentz force (equation 1.10) helps to describe this motion;

\[ \mathbf{F}_L = q \left( \mathbf{E} + \mathbf{v} \times \mathbf{B} \right) \]
where \( \mathbf{v} \) is the velocity of the particle when exposed to an electric field \( \mathbf{E} \) and a magnetic field \( \mathbf{B} \). The Lorentz force causes charged particles to move around magnetic field lines. Equation 1.10 shows that the force experienced by the particle is perpendicular to its motion and the direction of the magnetic field; this means that the Lorentz force doesn’t change the magnetic field-aligned particle speed.

### 1.1.2.1 In a Uniform Magnetic Field

If there is no electric field, equation 1.10 can be re-written as equation 1.11 and then differentiated over time to give equation 1.12

\[
m \frac{d\mathbf{v}}{dt} = q \mathbf{v} \times \mathbf{B}
\]

\[1.11\]

\[
\frac{d^2 \mathbf{v}}{dt^2} = -\left(\frac{qB}{m}\right)^2 \mathbf{v}
\]

\[1.12\]

where \( m \) is the mass of the particle.

Equation 1.12 describes the motion of the particle in a uniform magnetic field. It takes the form of a simple harmonic oscillator, showing that in a uniform magnetic field the particle follows a cyclical path perpendicular to \( \mathbf{B} \). The frequency of this simple harmonic motion is given by

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

\[1.13\]
The frequency \((\omega_g)\) is known as the gyro-, cyclotron or Larmor frequency.

From the definition \(v_\perp = r\omega\) (where \(v_\perp\) is the perpendicular velocity component) it is easy to see that the radius of this gyrotropic motion is

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

where \(r_g\) is the gyro- or Larmor radius. The centre of curvature is known as the particle's guiding centre, as shown in figure 1.

In the same B field, electrons gyrate one way and ions gyrate in the opposite direction. The different mass and charge between ions and electrons affect the size of their gyroradii. In the case of ions the size of the gyroradius depends

---

**Figure 1:** The sense of motion for an electron and an ion if the magnetic field is coming out of the page. The guiding centre is labelled for each case and the direction of the force is shown and labeled in red.
also on the degree of ionisation, i.e. $q$. The radius of the orbit is also dependent on the magnetic field strength.

When only a perpendicular component of velocity is present the particle will gyrate in circular orbits about, and perpendicular to, the magnetic field. When a parallel component is also present the particle would still move around the B field, but also along it, hence the motion evolves from a circle into a helix.

The angle defined by the ratio between the perpendicular and parallel velocity components is called the pitch angle, as described in equation 1.15.

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

where $v_\parallel$ is the parallel velocity component. The pitch angle varies depending on the motion of the particle. If a pitch angle is 0 or 180 degrees the particle is field aligned and moving either towards or away from the magnetic North Pole. If the pitch angle is 90° and if the particle is in a uniform magnetic field, the particle has no parallel velocity component so gyrate in a fixed plane perpendicular to the B field and is said to be trapped. A measurement in between, for example a pitch angle of 60°, means the particle has a combination of both parallel and perpendicular velocity components and thus travels in a helical manner, with its guiding centre at its focus.

Charged particles are able to drift due to various forces acting on them, including gravity. However, in space plasma physics, there are three drifts that are of greater importance; one in a uniform magnetic field and two in a non-uniform magnetic field.
If an electric field is now added into the scenario the particle will not follow a simple helix about the magnetic field. For a general force, the equation can be written in terms of the drift velocity of the guiding centre, as in equation 1.16.

\[ v = \frac{F \times B}{qB^2} \]

1.16

This general drift velocity is charge dependent so electrons would drift one way and ions in another.

1.1.2.2 DRIFT MOTION IN A UNIFORM MAGNETIC AND ELECTRIC FIELD

1.1.2.2.1 THE “E × B” DRIFT

When an E field and a B field are considered, equation 1.16 evolves into equation 1.17.

\[ v_{E \times B} = \frac{E \times B}{B^2} \]

1.17

Equation 1.17 describes the “E × B” drift, where \( v_{E \times B} \) is the drift velocity. The movement of the particle guiding centre will be in a direction perpendicular to both the electric field and the magnetic field. The “E × B” drift is visualized in figure 2.
The “\(E \times B\)” drift is a drifting of the guiding centre; when the electric field is perpendicular to the magnetic field the particle will experience higher centripetal acceleration during one side of the orbit. This increases and decreases the gyroradius, causing the drift of the particles’ guiding centre in the \(E \times B\) direction. \(v_{E \times B}\) is charge- and mass-independent and so will have the same magnitude and direction for both electrons and ions. Thus no net current arises from this type of drift motion.

Figure 2: The motion of an electron and an ion due to the “\(E \times B\)” drift. These gyroradii are not to scale.
1.1.2.3 **Drift motion in a non-uniform magnetic field**

1.1.2.3.1 **Gradient and curvature drifts**

A non-homogenous magnetic field is more typical in planetary magnetospheres so it is important that this scenario is discussed. If a magnetic field has a gradient (due to a change in field strength) perpendicular to the field, the particles that gyrate encounter this gradient and this affects their gyroradii. Because this concerns particles gyrating around the magnetic field, only the perpendicular component of velocity is considered. As seen in equation 1.14 the gyroradius is inversely proportional to the magnetic field strength. This means that for a stronger field the gyroradius is small and for a weaker field the gyroradius is larger. As for the $E \times B$ drift, these spatial variations result in orbits that do not close and a guiding centre that drifts. The drift velocity, $v_{VB}$, for the gradient drift is given by equation 1.18.

$$v_{VB} = \frac{mv_\perp}{qB^3} (B \times \nabla B)$$

1.18

The gradient drift for electrons and ions is shown in figure 3.
The gradient drift is charge dependent so ions and electrons would drift in opposite directions when there is a gradient in field strength that is perpendicular to the field direction. The gradient drift causes the differential motion of charged particles and therefore an electric current.

A perpendicular gradient in \( B \) is not the only thing that can occur; the \( B \) field is also able to curve, such as in a dipole field, i.e. a parallel gradient. The particles feel a force due to the curvature of the field and the force acts perpendicular to the magnetic field. The curvature drift is only relevant for particles travelling along the field line, thus only the parallel component of velocity is considered. Equation 1.19 defines the curvature drift velocity, \( v_C \).
The particles drift due to the force exerted on them, in a direction perpendicular to the magnetic field and the curvature of the field. The curvature drift is charge dependent, so ions and electrons will flow in opposite directions, which also means that a current is set up due to the curvature drift.

In order to satisfy the condition in equation 1.7, the magnetic field is both curved and possesses a gradient (although a perfectly uniform \( B \) has a divergence force), so the curvature drift and gradient drift velocities are combined to make a general magnetic drift velocity, \( v_M \).

When a general magnetic drift velocity is acting, the movement of individual particles along a field line can alter significantly. This is often the case in a planetary dipole where field lines converge to form a gradient in field strength.

In order to ensure the overall energy of a particle remains constant when travelling in such field lines, the concept of adiabatic invariants is defined.

To aid the understanding of the behaviour of particles on these field lines, the magnetic moment, \( \mu \), defined in equation 1.20, is taken into consideration. The magnetic moment is known as the first adiabatic invariant.

\[
v_C = \frac{m v_{\parallel}^2}{q B^4} (B \times (B \cdot \nabla)B)
\]

\[
\mu = \frac{1}{7} \frac{m v_{\perp}^2}{B}
\]
The magnetic moment is associated with individual particles and their gyromotion. If the first adiabatic invariant is conserved, \( \mu \) is constant thus any changes in the magnetic field that affect the particle's motion are gradual in comparison to the gyroradius and gyration period of that particle. The total magnetic flux within the gyro orbit radius therefore must remain constant, so if the magnetic field strength increases the particle acts to decrease its gyro motion. If there are no other forces acting on the particle its total kinetic energy will also remain constant.

If the guiding centre of a particle follows a path along an inhomogeneous magnetic field to an area of higher magnetic field strength, the perpendicular energy must increase. If the total kinetic energy remains constant, this must mean that the parallel kinetic energy decreases. When the parallel kinetic energy equals zero the particle only has a perpendicular energy component and the particle reverses direction.

This can also be shown by expressing the equation for magnetic moment as a function of the pitch angle, as shown in equation 1.21, which shows that when the pitch angle reaches an angle of 90° the particle reflects.

\[
\mu = \frac{\mu_1 mv^2 \sin^2 \alpha}{B}
\]

1.21

This reversal of motion is known as magnetic mirroring because the particle is reflected back along the field line until it encounters a similar geometry, usually at the other end of a planetary dipole field line. A magnetic mirror is shown in figure 4.
The effective force exerted on the particle’s guiding centre can be defined by equation 1.22 and acts in the opposite direction to the gradient in the magnetic field strength, where $s$ is distance measured along the magnetic field line.

$$F_s = -\mu \frac{dB}{ds}$$

1.22

The particles travel along the dipole field lines, between the equatorial plane and the mirror point, then back again. The period of this motion in a dipole field is called the bounce period, as expressed in equation 1.23, and is the time taken for the particle to travel from the equator back to the equator via both mirror points.
$\tau_b \sim \frac{LR}{W/m} (3.7 - 1.6 \sin \alpha_{eq})$

where $\alpha_{eq}$ is the equatorial pitch angle, $W$ is the total kinetic energy of the particle and $L$ is the McIlwain parameter, or $L$ shell, which is the distance to a magnetic field line from the centre of the planet, measured in the magnetic equatorial plane, in units of planetary radii. For a dipole magnetic field the $L$ value can be found by using equation 1.24, where $r$ is the radial distance, $L$ is the $L$ shell and $\lambda$ is the magnetic latitude.

$$r = L \cos^2 \lambda$$

Two magnetic mirrors located at opposite ends of the same field line or along the same field line create a magnetic bottle. A particle can become trapped in such a bottle when a minimum magnetic field is found between the mirror points and maximum magnetic field at the mirror points. In this situation the particle bounces between both points. At each mirror point the pitch angle tends to 90°. If a particle satisfies the inequality in equation 1.25, the particle is said to be trapped. $B_{max}$ in equation 1.25 denotes the magnetic field strength at the mirror point. Figure 5 shows a trapped particle trajectory in the Earth’s magnetosphere.

$$\mu > \mu_{trapped} = \frac{1}{2} \frac{mv_{total}^2}{B_{max}}$$

1.23

1.24

1.25
Trapped particles exhibit bounce motion up and down the magnetic field lines between mirror points, but there is an exception. A magnetic mirror is not able to trap a charged particle which moves with an adequately small pitch angle. This area where the particles are able to be scattered or escape is called a *loss cone*. The size of the loss cone may be defined by the range of equatorial pitch angles for which particles are not seen in the magnetosphere, i.e. $0 \leq \alpha_{eq} \leq \alpha_{loss}$.

This is applicable for particles moving along the field lines in either direction, so the range of equatorial pitch angle is $180^\circ \geq \alpha_{eq} \geq 180^\circ - \alpha_{loss}$.

An example how a loss cone may arise is when electrons encounter neutrals in the ionosphere and are thus absorbed or scattered by collisions with these neutrals within a few bounces between magnetic mirror points.

The angle of a loss cone can be calculated, for a dipole field, using equation 1.26, and depends only on field line dimension, not on the energy of a particle.
This means that all particles on a given field line have the same size of loss cone, regardless of their properties.

\[ \sin^2 \alpha_{\text{loss}} = (4L^6 - 3L^5)^{\frac{1}{2}} \]

1.26

There are two other adiabatic invariants. The second concerns \( J \), which is the longitudinal invariant of a particle which is trapped and bouncing in a magnetic bottle, as shown in equation 1.27, where \( S \) is a distance.

\[ J = \int v_h \, dS \]

1.27

If a charged particle is trapped in the field of a planet its trajectory will not completely close due to the azimuthal drift of particles around the planet. If the second adiabatic invariant is conserved, the trapped particle will always return to the same line of force.

The third invariant, \( \Phi \), is the total magnetic flux enclosed by the drift trajectory, and this will be a constant provided that changes in the field affecting the particle are slow in comparison to the drift period. A consequence of the third invariant is that when trapped particles are drifting and have a periodic motion, the total magnetic flux enclosed by the drifting surface remains constant. This implies that a particle will alter its orbit to maintain the total magnetic flux, i.e. if the magnetic field strength reduces the particle will tend to orbit at a larger radial distance to conserve flux.
1.1.3 **Kinetic Theory and the Many Particle Motion Approach**

Whilst the consideration of single particle motion has its uses in determining the trajectories of individual ions and electrons in a plasma, it is not always possible to consider a plasma as a large number of individual particles and, instead, it becomes necessary to describe the plasma in a statistical way. The position and velocity of each particle at each point in time is used to define the six-dimensional (3 space and 3 velocity) *phase space* of the system. Thus the plasma, and its characteristics, can then be considered as a distribution function of particles. Each of the space and velocity points is considered to be a point in phase space which can be followed as a particle trajectory, giving information about the system as it changes over time. However there are often too many particles to consider the individual trajectories so the phase space density of particles (the number of particles in a volume element of phase space) is generally used. The particle distribution function is integrated over the velocity element of phase space in order to find properties such as number density and temperature of the plasma. These properties are called the moments of the distribution function; the process of deriving their values is further described in chapter 3.

1.1.4 **Magnetohydrodynamics**

In addition to kinetic theory, plasma can also be considered as a collection of particles comprising a magnetised fluid. For this to be valid some constraints must be met. The fluid processes must occur over a large system with scale sizes greater than the gyroradius and in relation to the gyration frequency of
the particles, the fluid properties must change slowly. If these characteristics are present, magnetohydrodynamics (MHD) can be used to describe the plasma. Another constraint is that the fluid elements must be much smaller than the length scales of the changes to the system. MHD is applicable if the length scale of changes in pressure, temperature etc. is much larger than the gyroradius.

Because MHD considers a magnetic and electrically conducting fluid, it applies fluid dynamic equations, such as the Navier-Stokes equations, and Maxwell’s equations to the plasma; these equations are described in section 1.1.4.1.

1.1.4.1 MHD EQUATIONS

The equations of ideal MHD are given in this section. These equations are valid when the fluid is assumed to be a perfect electrical conductor and the magnetic Reynolds number (discussed in section 1.1.4.3) is very large. The equations can be written for a single particle species (single fluid MHD) or for many species (multi fluid MHD). For simplicity here the equations are written generally, assuming quasi-neutrality, such that $n=n_e=n_i$ (number density of electrons and ions respectively).

The mass continuity equation (equation 1.28) describes conservation of mass and is obeyed if the mass is conserved when the fluid is in motion, and if no source or loss processes are in force.

$$\frac{\partial \rho}{\partial t} + \nabla (\rho \mathbf{v}) = 0$$
The **momentum equation or equation of motion** is stated in equation 1.29.

\[
\rho \frac{\partial \mathbf{v}}{\partial t} + \rho (\mathbf{v} \cdot \nabla) \mathbf{v} = -\nabla \cdot \mathbf{P} + (\mathbf{j} \times \mathbf{B})
\]

1.29

This can also be written in an extended form as equation 1.30

\[
n \left( \frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} \right) + \frac{1}{m} \nabla \cdot \mathbf{P} - \frac{q}{m} n (\mathbf{E} + \mathbf{v} \times \mathbf{B}) = 0
\]

1.30

Pressure and number density are related by the power law, \( p \propto n^\gamma \). When isotropic pressure is assumed the polytropic index, \( \gamma \), is taken to equal 5/3, indicating that the plasma behaves adiabatically, i.e. no heat is transferred. If other forces, such as the effects of viscosity, are present an additional term can be added to equation 1.30.

**1.1.4.2 Evolution of Ohm’s Law**

When dealing with a multi fluid approach (electrons and protons, for example) a relationship between the electric field and current density can be derived by subtracting the motion equations for electrons from the motion equations for ions. The relationship is called the **generalised Ohm’s law** and is given in equation 1.31.

\[
\mathbf{E} = (-\mathbf{v} \times \mathbf{B}) + \left( \frac{1}{\sigma} \mathbf{j} \right) + \left( \frac{1}{ne} \mathbf{j} \times \mathbf{B} \right) - \left( \frac{1}{ne} \nabla p_e \right) + \left( \frac{m_e}{ne^2} \frac{\partial \mathbf{j}}{\partial t} \right)
\]

1.31
In equation 1.31 $j$ is the current density, a measure of the net flow of charge, and $1/\sigma = \eta$ which is the resistivity of the plasma ($\sigma$ is electrical conductivity).

The first term on the right hand side is the motional electric field. The second term is the “Ohmic term” which includes the current density and the resistivity terms. The third term is the Hall term, giving an electric field perpendicular to the current density and the magnetic field. The fourth term is the ambipolar electric field due to a gradient in the pressure and the final term contains the time variation of current density, often referred to as the electron inertia.

It is possible, for many cases in a magnetosphere, to ignore many terms on the right hand side of the equation because they are insignificant compared to the term on the left hand side. This gives equation 1.32 which relates the current density to the electric field at rest and in motion.

$$\eta j = E + v \times B$$

Plasma resistivity varies as a function of collision frequency ($\eta = m_e v / n e^2$) and in near collisionless plasmas the frequency is very small, but not zero. This leads to a small resistivity and hence a large conductivity. This gives equation 1.33, which is a particularly useful version of Ohm’s law, in which $\eta=0$.

$$E = -v \times B$$

If the ideal MHD conditions are met equation 1.33 describes the frozen in flux theorem. The idea behind this theorem is that when the plasma moves, the
magnetic field follows such that the plasma particles are ‘frozen’ to the same field line. This is described more in section 1.1.4.3.

1.1.4.3 The induction equation and frozen in flux

Equation 1.32 can be re-written as equation 1.34.

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

1.34

Then, Ampère’s law can be used to substitute for \( j \) and \( \mathbf{E} \) is substituted using Faraday’s law. Vector identities are utilised to produce equation 1.35.

\[ \frac{\partial \mathbf{B}}{\partial \tau} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \frac{1}{\mu_0 \sigma} \nabla^2 \mathbf{B} \]

1.35

Equation 1.35 is the induction equation, also known as the hydromagnetic or dynamo equation. The first term on the right hand side is the convective term and the second term on the right hand side is the diffusive term.

If a plasma is collisionless, the convective term dominates the behaviour of the \( \mathbf{B} \) field. The field moves with the plasma and magnetic flux through a moving fluid element is invariant under typical conditions, however eventually, due to collisions, a resistivity builds up and the diffusion term becomes significant again, breaking down the ideal MHD theorem. Diffusion (of fields or plasma) is important as it causes the breakdown of the frozen in theorem and allows reconnection to occur.
### 1.1.4.4 Magnetic Reynolds Number

The ratio between the convection and diffusion terms in the induction equation is the magnetic Reynolds number, as expressed in equation 1.36.

\[
R_m = \frac{\nabla \times (\mathbf{v} \times \mathbf{B})}{\frac{1}{\mu_0 \sigma} \nabla^2 \mathbf{B}}
\]

1.36

The magnetic Reynolds number can be rewritten using a dimensional analysis. This is shown in equation 1.37

\[
R_m = \frac{L \mathbf{v}}{\eta}
\]

1.37

where \( L \) is the length scale over which changes in the fluid dominate. If \( R_m \gg 1 \) the convective term dominates and the plasma is frozen to the magnetic field, following the ideal MHD description. For a near-collisionless plasma the magnetic field can vary over large spatial scales. This also gives a large \( R_m \) and an ideal MHD assumption. If \( R_m \ll 1 \) the diffusion term dominates and timescales for diffusion can be calculated using equation 1.38.

\[
t_d = \frac{L^2}{\eta} = \frac{L}{\mathbf{v} R_m}
\]

1.38
1.1.4.5 Uses of the MHD Equations

The Lorentz force was first mentioned in equation 1.10, and is the addition of magnetic pressure and magnetic tension in a field line. These two MHD concepts can be derived from Ampère’s law. The current density is substituted from the MHD equations by combining the momentum equation with Ampère’s law (equation 1.39).

\[
\mathbf{j} \times \mathbf{B} = \frac{1}{\mu_0} (\nabla \times \mathbf{B}) \times \mathbf{B}
\]

1.39

This can be rewritten as equation 1.40:

\[
\mathbf{j} \times \mathbf{B} = -\nabla \left( \frac{B^2}{2\mu_0} \right) + \frac{1}{\mu_0} (\mathbf{B} \cdot \nabla)\mathbf{B}
\]

1.40

The first term on the right hand side of equation 1.40 is the force exerted by a gradient in the magnetic flux density (i.e. magnetic field strength) which dimensionally corresponds to the magnetic pressure in equation 1.41.

\[
p_{mag} = \frac{B^2}{2\mu_0}
\]

1.41

The second term on the right hand side of equation 1.40 is the magnetic tension force. This is the force exerted on a plasma due to the tendency for a bent or distorted field line to change shape to return to its minimum length and to straighten out.
The magnetic pressure term, $p_{\text{mag}}$, and the plasma pressure term, $p$, are summed to describe total pressure, but the ratio of these gives the plasma beta (equation 1.42).

$$\beta = \frac{2\mu_0 p}{B^2}$$

The plasma beta is an important parameter as it reveals whether the system is controlled by the magnetic field or the plasma pressure. If $\beta > 1$ the particle pressure dominates and the system is in a high beta regime. If $\beta < 1$ the magnetic pressure dominates and the system is in low beta regime.

A force free magnetic field system is one in which the plasma pressure is small compared with the magnetic pressure, such that only the magnetic pressure is considered. The reason it is called force free is because in this system it is possible to neglect the force from the plasma.

The force free condition can be derived, starting with the simplified magnetostatic equation, neglecting the effects of gravity.

$$0 = -\nabla p + j \times B$$

If the plasma pressure term is very small it can be neglected, giving equation 1.44.

$$0 = j \times B$$
Equation 1.44 can be said to show that the current is parallel to the magnetic field, when written as equation 1.45, where \( \alpha \) is a scalar function that varies with position and time.

\[
\mu_0 j = \alpha B
\]

Using Maxwell’s equations 1.7 and 1.9 and the vector identity \( \nabla \cdot (\nabla \times B) = 0 \) it is possible to get to equations 1.46 and 1.47.

\[
B \cdot \nabla \alpha = 0
\]

\[
\nabla \times B = \alpha B
\]

These equations are the force free equations, in which \( \alpha \) is constant along each field line.

1.2 Planetary magnetospheres
1.2.1 The solar wind

The solar wind is a stream of charged particles emanating from the Sun and flowing radially away from it, dragging with it a magnetic field. It can be considered an extension of the solar corona into interplanetary space.
The electrons and ions that make up the solar wind also flow out into interplanetary space. The solar wind was first suggested by Ludwig Biermann in the early 1950s. Biermann noticed that comet tails don’t point exactly away from the Sun, but are tilted by a few degrees from the radial direction, so the solar wind has to have a moderate, rather than an infinite, speed. Eugene Parker was the first to use the moniker “solar wind” and he was able to show that the solar corona is so hot that the particles that make up the outer corona become supersonic and can overcome the pull of gravity and escape into space [Parker, 1958]. The solar wind is highly conductive which means that the frozen in flow condition is met, thus the magnetic field of the Sun is pulled along with the solar wind into interplanetary space as well. This field is called the Interplanetary Magnetic Field (IMF) (also sometimes called the heliospheric magnetic field or HMF). The magnetic field lines are embedded deep within the Sun and thus rotate with it and the combination of the solar

![Figure 6: A cartoon showing the Sun with the heliospheric current sheet, the three dimensional boundary between outward and inward polarity of the magnetic field. Its shape generally follows the Parker spiral. Courtesy of NASA.](image)
rotation and the outward motion of the solar wind forces the field into a spiral
pattern, called the Parker spiral [Parker, 1958]. The heliospheric current sheet
is shown in figure 6. The undulations in the heliospheric current sheet follow
the Parker spiral. The consequence of the change of the ‘pitch’ of the Parker
spiral with heliocentric distance is that the IMF reaches different planets at
different average inclinations to the antisunward direction, depending on how
far away the planet is. Solar wind characteristics and Parker spiral angles for
Earth and Saturn are discussed in section 2.2.2.

The sources for the fast solar wind are believed to be regions of open magnetic
field at higher latitudes, called coronal holes, whereas the slow solar wind is
thought to originate from closed coronal magnetic field, from lower latitudes.
However, the locations of these regions depend on the solar cycle as it is
possible to get coronal holes at the equator at times, and the slow solar wind
has been measured to emanate from the poles during solar maximum [Bzowski
et al., 2003].

1.2.2 PLANETARY MAGNETIC FIELDS

The magnetic field of a planet can be calculated and expressed in a
mathematical form. It can be described as the gradient of a scalar potential,
portraying the contributions from internal and external sources.

\[
V_{int} = \frac{4\pi}{\mu_0} a \sum_{n=0}^{\infty} P_n^m (\cos \theta) \left[ g_n^m \cos m\phi + h_n^m \sin m\phi \right]
\]
Equation 1.48 shows the total internal contribution to the total magnetic field. \( V_{\text{int}} \) is the scalar potential and \( m \) and \( n \) are order and degree of the Legendre function \( P^m_n \). \( a \) is the radius of the planet at the equator and \( \theta \) and \( \phi \) are the polar and azimuthal angles respectively. \( g^m_n \) and \( h^m_n \) are the Gauss coefficients and are determined from fitting data. For the simplest case, an axially symmetric dipole, \( m=0 \), \( \sin m\phi=0 \) and \( \cos m\phi=1 \), which gives the scalar potential in equation 1.49.

\[
V_{\text{int}} = \frac{g^0_1 \cos \theta}{r^2}
\]

1.49

If the gradient of \( V_{\text{int}} \) is taken, the vector components of the magnetic field (\( B_r \), \( B_\theta \) and \( B_\phi \)) emerge.

1.2.3 **Planetary Magnetospheres**

Planetary magnetospheres arise due to an internal dynamo inducing a magnetic field within a planet. These magnetic fields interact with the solar wind, creating a cavity in which the planet is contained; this is known as the magnetosphere. Generally magnetospheres are specific to planets with intrinsic magnetic fields but the environments around weakly magnetised and non-magnetised bodies such as Venus, Mars and comets are able to deflect the solar wind sufficiently that they can be considered to have a pseudo or induced magnetosphere.
A general, simple, closed magnetosphere model is shown in figure 7. The Sun is on the left hand side, the solar wind flow is shown by the thick black arrows and the different sections of the magnetosphere are labelled.

![Figure 7: A schematic of a generalized magnetosphere, with different regions labeled. The thick black arrows show the flow of the solar wind, with the Sun on the left hand side. From [Kivelson & Russell, 1995]](image)

A closed magnetosphere is one in which no magnetic field lines cross the magnetopause, i.e. the component of B that is normal to the boundary is zero. The solar wind and IMF cannot enter the magnetosphere because of the frozen in flux approximation. The planetary magnetic field is confined by the current sheet flowing on the magnetopause. The application of Ampère’s law across the boundary shows that the magnetopause must carry the current, demonstrated in figure 7 flowing into and out of the page with ⊗ and ⊙ respectively. The amount of plasma that can enter the magnetosphere depends on whether the
magnetosphere is open or closed. In an open magnetosphere the IMF is able to
cross the magnetopause boundary. The reason the magnetosphere can take on
an ‘open’ configuration is due to magnetic reconnection, which will be
discussed in section 1.3.2.

1.2.3.1 The Bow Shock

The solar wind is supermagnetosonic; its fluid velocity surpasses the
magnetosonic speed. This can be described using the Alfvén speed, which is
analogous to the sound speed in a classical ideal gas. The Alfvén speed is shown
in equation 1.50 and can be found by equating the left hand side of the equation
of motion (1.29) with a fluid Lorentz force.

\[v_A^2 = \frac{B^2}{\mu_0 nm}\]

1.50

The Alfvén speed is the speed at which information travels in a magnetised
plasma, along the direction of the magnetic field. If the Alfvén speed
approaches the speed of light, the Alfvén wave propagates as an ordinary
electromagnetic wave.

The magnetosonic speed, \(c_{MS}\), is the square root of the sum of the sound speed
squared plus the Alfvén speed squared. The magnetosonic Mach number is the
ratio between the plasma fluid speed, \(v\), and the magnetosonic speed, as shown
in equation 1.51.
Because the solar wind is supersonic, if it encounters an obstacle, a plasma shock forms upstream. This shock wave is known as the *bow shock*. The Earth and other magnetized planets are obstacles to the solar wind and, due to the frozen-in theorem, plasma trapped on specific magnetic field lines cannot (in general) mix with other plasma populations. This means that $M_{MS} > 1$ and whenever this condition is met a shock will form upstream of the stationary obstacle. The supersonic property of the solar wind means that details of the obstacle downstream from the shock can't be relayed upstream to incoming particles; hence they are not able to divert their paths.

### 1.2.3.2 The Magnetosheath

At the bow shock the solar wind particles are deflected, heated and slowed rapidly by the shock from a supersonic to a subsonic flow. The kinetic energy of the particles is partly transformed to thermal and magnetic energy. This transformation causes the bulk plasma to have increased density and temperature compared to the upstream solar wind because the overall pressure on either side of the bow shock must be conserved. This region containing the shocked solar wind plasma is known as the *magnetosheath*. Because the flow of this plasma is subsonic the plasma is able to smoothly divert about the obstacle. The magnetic field magnitude also increases within the magnetosheath due to the increased density of the plasma and the frozen in theorem. The thickness of the magnetosheath depends on the
speed of the solar wind. The magnetosheath is important because it borders the region dominated by the planetary magnetic field, the magnetosphere. The magnetosheath is where the solar wind and hence the IMF is redirected to pass around the obstacle, influencing the orientation of the IMF as it reaches the magnetopause of the planet. The solar wind compresses the magnetosphere on the side of the planet closest to the Sun, the dayside, by resulting in IMF draping. The opposite side of the magnetosphere, the nightside, is elongated in the solar wind flow and the magnetosphere is stretched into a tail like configuration, which can, depending on the size of the planet, reach hundreds of planetary radii away from the planet itself.

1.2.3.3 The Magnetopause and the Cusps

The magnetopause characterises the boundary between the planetary magnetosphere and the IMF; due to the frozen in flow theorem the two are not generally able to merge. The magnetopause is a boundary for momentum and energy exchange between the planetary plasma and magnetic field and those from the Sun. Its existence was first proposed by Chapman and Ferraro in 1931, who spoke about a current layer between the planet and the Sun, impeding the penetration of the solar wind into the planet's field. This current layer is the magnetopause. The formation of the current layer is also a product of the frozen in flow theorem; the non-mixing of the IMF and the planetary magnetic field creates a gradient in the magnetic field at the boundary and, by Ampère’s law, this gradient induces a current. The induced current layer is a thin current sheet separating the planetary magnetic field and the IMF.
In an open magnetosphere, the frozen in theorem breaks down and the solar wind is able to penetrate the magnetospheric field at high latitudes. Magnetosheath plasma thus has direct access to the planetary ionosphere. The polar regions in which this is occurring are called the cusps. These are cone shaped structures at the magnetic poles of the planet and are important as it is here that solar wind plasma can penetrate into the magnetosphere.

![Figure 8: The Chapman Ferraro magnetopause current layer, showing how the charge of a particle can cause separation and a current layer which is one gyroradius thick. From [Kivelson & Russell, 1995](#)](image)

The simplest picture of the magnetopause is the Chapman Ferraro model, shown in figure 8. This model neglects the magnetospheric plasma and the
solar wind magnetic field. Particles enter the magnetopause current layer and experience the planetary magnetic field. The Lorentz force causes them to complete half a gyroradius and then return to the solar wind. The width of the magnetopause is hence dependent on the gyroradius of the particles which enter it. The current arises because ions gyrate in one direction and electrons in the opposite direction so their charges move apart before returning to the solar wind. The current naturally has a magnetic field associated with it, which generates a diamagnetic effect, confining the planetary magnetic field inside the magnetopause so that it is not detected in the magnetosheath or the solar wind.

The simplest approximation of the location and size of a magnetopause is found by applying a pressure balance between the planetary field and the solar wind. At the magnetopause the solar wind plasma pressure (thermal plus dynamic) and the magnetic pressure outside the magnetosphere are considered to be in equilibrium with the magnetospheric plasma pressure and interior magnetic pressure inside the magnetosphere.

Generally, outside a magnetosphere, the plasma pressure dominates because the magnetic pressure can be regarded as negligible. The plasma pressure is made up of two components: the dynamic pressure and the thermal pressure. In the solar wind the majority of the energy is in the bulk motion of the plasma, so only dynamic pressure is considered.

Inside the magnetosphere the magnetic field pressure dominates because the plasma pressure is small by comparison, so only the magnetic pressure term is considered. This simplifies the pressure balance equation significantly. Another
simplification is to apply it at the subsolar point, which yields a magnetopause standoff distance; the distance between the nose of the magnetopause and the planet.

1.2.3.4 The Inner Magnetosphere

The inner magnetosphere is home to the plasmasphere, an area of closed field lines located, in the terrestrial magnetosphere, close to the planet. These field lines are where low energy plasma lies on closed drift paths around the planet, forming a toroidal region containing cold magnetospheric plasma, which corotates with the planet. Corotation occurs due to the interaction between the atmosphere and the magnetosphere of a rotating planet. Collisions between neutral species and ions cause the ionosphere to corotate with the atmosphere. Currents which flow between the ionosphere and magnetosphere then impose corotation on the entire plasmasphere.

The ring current is situated slightly further out from a planet in its magnetosphere and is important for inner magnetosphere dynamics as it is generated by high energy plasma drifting around the planet due to curvature and gradient forces. The drifting of electrons in one direction and ions in the opposite direction leads to a net flow of charge and hence an electric current.

1.2.3.5 The Magnetotail

On the dayside (towards the Sun) the magnetosphere is compressed due to the solar wind exerting a force on it. In a ‘closed’ magnetospheric configuration the
solar wind flow stretches the nightside (away from the Sun) magnetosphere into a tail-like formation, the magnetotail.

The magnetotail comprises four main sections: the plasma (or current) sheet which is a region of high plasma pressure, the tail lobes, the closed magnetic field lines and the tail portion of the magnetopause.

The plasma sheet is a region of hot, high density plasma and low magnetic field. Within the plasma sheet a neutral sheet is created due to the field changing direction between the northern and southern hemisphere. The field strength drops to near zero in this region. The tail lobes are separated from the plasma sheet by the plasma sheet boundary layer and contain low density plasma and a relatively strong magnetic field.

1.3 Dynamics of the Magnetosphere

1.3.1 Currents

Currents are induced whenever a magnetic field varies, which happens often in a planetary magnetosphere. Using Ampère’s law it can be seen that many current systems in a planetary magnetosphere can be induced. These currents help to act as a barrier to the solar wind and interplanetary magnetic field. The major currents which exist in a magnetosphere are the magnetopause current, the tail current, the neutral sheet current and the ring current. The magnetopause current travels from dawn to dusk for Earth, and in the opposite direction for Saturn because the polarity of the magnetic field is reversed, closing in the nightside via the tail current. The tail current is due to the change in direction of the magnetic field of the magnetotail across the neutral sheet; a
spatial gradient in the magnetic field is associated with a current. The currents in the tail, when viewed from the tail looking at the planet, make a $\theta$ shape. Other currents also exist in a magnetosphere, such as Birkeland currents which are field aligned currents that connect the ionosphere to the magnetosphere. They are caused by the closure of ionospheric currents which flow perpendicular to the magnetic field. Currents play an important part for the dynamics of a magnetosphere and are shown in the magnetosphere in figure 9.

Figure 9: a schematic showing the currents that are present in the Earth's magnetosphere. From [Stern, 1994].

1.3.2 **Reconnection**

Magnetic reconnection is a mechanism in which oppositely directed magnetic field lines interact in such a way that they are pushed together and reconnect, resulting in a new magnetic field topology. In areas of high magnetic Reynolds
number, particles are frozen on to magnetic field lines and thus cannot mix. Magnetic reconnection occurs in low magnetic Reynolds number areas, where the diffusion term surpasses the convection term, causing the frozen-in flux conditions to break down. When the frozen in flux conditions break down, particles no longer adhere to magnetic field lines and the field moves through the plasma, meaning that reconnection can more easily occur.

Reconnection can occur when two opposing field lines separated by a thin current sheet are brought together due to the solar wind, IMF or planetary fields. The breakdown of the frozen in flux conditions causes the current sheet to develop a finite conductance, allowing a diffusion region to be created over which the fields are able to diffuse, meet and reconnect. The position of reconnection is called the ‘X’ line and the new field lines are bent towards it. The new field lines are subject to magnetic forces such as the tension force, thus become straightened away from the ‘X’ line, and the whole process can begin again. The process of reconnection releases magnetic energy which can be transferred to the plasma. When the bent, new field lines become realigned, the particles that are frozen onto the field lines will be accelerated, transferring the magnetic energy into kinetic energy and thermal energy. This process is shown in figure 10.
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Two models of magnetic reconnection are discussed here; the Sweet-Parker model and the Petschek model. The Sweet-Parker model portrays a reconnection which is time independent, dealing with antiparallel magnetic fields but ignoring effects such as compressibility and viscosity. The diffusion region in this model is long and thin and the rate of diffusion depends on the inflow velocity of plasma to the diffusion region, which is a function of the Alfvén velocity and magnetic Reynolds number.

The Petschek model evolves the Sweet-Parker model by making it unnecessary for all the reconnected material to travel through the diffusion region to be accelerated. The Petschek model relies on shocks at the ‘X’ line to accelerate the material. This means the diffusion region can be smaller and hence, the reconnection rate increases. This is important because most Solar System reconnection rates are too high for the Sweet-Parker model to be a good explanation.

Figure 10: a cartoon showing how magnetic field lines form an X line and reconnect. This is a simplified 2-D picture.
1.3.3 **The Dungey Cycle and the Vasyliunas Cycle**

The Dungey cycle [Dungey, 1961], shown in figure 11, is the process of solar wind driven steady state magnetospheric convection that occurs due to magnetic reconnection.

![Diagram of the Dungey cycle](image)

**Figure 11:** The Dungey cycle at Earth. The solar wind impinges on the magnetosphere from left to right. The solid black lines show the IMF and planetary magnetic field lines. The numbers without a dash show how the planetary field lines change after reconnecting with an IMF field line (numbered with dashes).

*From* [Kivelson & Russell, 1995]*

The reconnection procedure starts on the dayside magnetopause when the IMF meets the planetary field lines for the first time (field line 1’ in figure 11).
Reconnection creates open magnetic field lines emanating from the ionosphere at high latitudes along the poles, out to the solar wind. The open magnetic field lines move with the solar wind and are taken to the nightside by the solar wind flow and the field line is stretched and becomes part of the tail lobes (field lines 2 – 5). In this way, more and more field lines are added to the tail. On the nightside the field line travels towards the centre of the tail, an 'X' line is formed, plasma is accelerated and reconnection occurs in the tail current sheet (field line 6). The newly closed field lines flow back towards the planet (field lines 7 and 8) and convect around the sides of the planet back to the dayside, completing the cycle. During the cycle, the accelerated plasma is sent, as a plasmoid, past the X line travelling tailward.

The Dungey cycle is controlled by solar wind and enabled by reconnection. It is particularly significant at Earth which is a slowly rotating planet without many internal plasma sources, and the debate continues about its importance at Jupiter and Saturn.

There is a second cycle at Jupiter; the Vasyliunas cycle [Vasyliunas, 1983], which occurs for fast rotators with strong magnetic fields and major plasma sources.
This cycle, shown in figure 12, is dominated by mass loaded field lines that stretch to the tail and plasmoids are released tailward as mass loading increases, so centrifugal forces are also important.

The magnetic field lines are stretched due to an addition of plasma (labelled 1 and 2 in figure 12). The magnetic field lines reconnect in the tail, forming a plasmoid (label 3). The plasmoid is released through the tail whilst the reconnected magnetic field lines snap back towards the planet and reconfigure (label 4) and the process begins again.

Whilst the two processes commence in different ways, the reconnection and plasmoid generation look very similar. At present there is evidence for both cycles at Saturn, due to the solar wind interaction and the dominant centrifugal forces. A new flow cycle, a combination of the two cycles, has been proposed and is shown in figure 13 [Cowley et al., 2004].
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It is interesting that the convection patterns at Saturn fall somewhere between Earth and Jupiter because the notion that Saturn's characteristics are somewhere between Earth-like and Jupiter-like will arise again in chapter 4.

1.4 SUMMARY

In this chapter, several aspects of space plasma physics and planetary magnetospheres have been introduced. In the following chapter the concept of Saturn's magnetosphere is described in detail, using knowledge from past and present space missions, and comparisons are made with the magnetospheres of Earth and Jupiter.
CHAPTER 2  \textbf{SATURN AND ITS MAGNETOSPHERE}

“It’s a big rock. I can’t wait to tell my friends. They don’t have a rock this big.”

Spike, BTVS, episode 2.21

Lying 9.5 AU ($1.496 \times 10^8$ km) away from the Sun is Saturn; a true jewel of our Solar System. Following an orbit inclined at 2° to the ecliptic, Saturn takes approximately 29.43 Earth years to orbit the Sun and has an equatorial radius of 60,268 km (= 1 Saturn radius = 1 $R_S$) at a pressure of 1 bar [Seidelmann et al., 2006]. Saturn, with an axial tilt of $\sim 26^\circ$ to its orbital plane, has by far the most extensive ring system in the Solar System, and is orbited by a plethora of moons (important in their own right). The kronian system thus resembles a miniature solar system nestled within our own. Saturn is largely gaseous, and is less dense, on average, than water; its mean density is 0.69 g/cm$^3$ [Hamilton, 1996]. It is believed to have a similar composition to Jupiter; a rocky core surrounded by a liquid metallic hydrogen layer and a gaseous atmosphere [Guillot et al., 2009]. The composition of the atmosphere is approximately 75% Hydrogen and 25% Helium [Fouchet et al., 2009].

Saturn has an intrinsic magnetic field, believed to be created by currents in the metallic hydrogen liquid layer, and hence its own magnetosphere. The kronian magnetosphere’s magnetic dipole moment is about 30 times smaller than that of Jupiter, but approximately 600 times stronger than that of Earth. It is the third largest magnetosphere in the Solar System after the Sun’s heliosphere
and Jupiter’s magnetosphere [Bagenal, 1992]. The magnetosphere extends sunward from the planet centre to the magnetopause nose which resides at a mean distance of 22 $R_S$, and tailward it extends past 50 $R_S$ [McAndrews et al., 2009]. The size and shape of the magnetosphere will be discussed in more depth in chapter 4. Figure 14 shows Saturn, the rings and the inner moons.
Figure 14: Saturn with the rings and inner moons. Relative distances are to scale.

Courtesy NASA/JPL.
2.1 History of Saturn Observations

Saturn has been an object of particular interest for over 400 years. In 1610 Galileo Galilei pointed his telescope at Saturn and saw what he interpreted as a planet ‘with ears’ or with two stationary moons. 46 years later Huygens realised that these ears were in fact the ring system recognisable to us today. Huygens also discovered Titan, Saturn’s largest moon, in 1655. This was followed by the discovery of the moons Iapetus, Rhea, Tethys and Dione by Cassini from 1671 to 1684. The small icy moons Enceladus and Mimas were discovered by Sir Frederick William Herschel in 1789.

In-situ space plasma physics followed many centuries later and the first spacecraft to visit Saturn was Pioneer 11 in 1979 [Acuña & Ness, 1980]. Pioneer 11 carried, amongst its instruments, a magnetometer, plasma analyser and charged particle analyser, primarily included for solar wind measurements. The flyby of Saturn by Pioneer 11 was fleeting but useful; Pioneer travelled through the ring plane in order to test a possible trajectory for the upcoming Voyager probes. Pioneer crossed the bow shock at 24 \( R_S \) at local noon then crossed the magnetopause at 17 \( R_S \). We now know that this is a relatively low standoff distance, indicating a high solar wind dynamic pressure compressing the magnetopause at that time. The spacecraft exited the Saturn system through the dawnside magnetopause at approximately 40 \( R_S \).

Voyagers 1 and 2 were next to encounter Saturn, in 1980 and 1981 respectively [Ness et al., 1981; Ness et al., 1982]. Again the spacecraft entered Saturn’s magnetosphere at noon with Voyager 2 exiting like Pioneer around the dusk.
flank, but Voyager 1 left further down tail at about 04:00 local time. Voyager 2 reached latitudes of up to 30°, whereas Voyager 1 remained near the equatorial plane. A diagram illustrating these spacecraft trajectories in a Sun-Saturn reference frame is shown in figure 15.
Figure 15: The trajectories of Pioneer 11, Voyager 1 and Voyager 2 spacecraft during their flybys of Saturn in the late 1970s and early 1980s. The plot is in the equatorial plane where X points along the Saturn-Sun line, Z is along the spin axis and Y completes the right-handed set. Bow shock crossings are denoted by the letter S and magnetopause crossings are denoted by the letter M. The thicker lines on the trajectories show the range of magnetopause crossings.

From [Sittler Jr et al., 1983].
These first flybys, whilst fleeting, were of importance in early magnetosphere studies. Pioneer was the first to detect the intrinsic magnetic field [Smith et al., 1980] and the Voyager probes gave data that enabled the measurement of the magnetic moment.

It would take more than twenty years for another mission to visit Saturn, but this time with an orbiting spacecraft in the form of Cassini. Cassini arrived at Saturn in 2004 and the data collected by the spacecraft since then has aided scientists in deducing invaluable information about Saturn and its magnetosphere, enhancing our knowledge and widening the dataset nearly continuously since orbit insertion. The relevant Cassini instruments will be discussed in greater detail in chapter 3.

2.2 SATURN’S MAGNETIC FIELD AND MAGNETOSPHERE

2.2.1 MAGNETIC FIELD

The strength of Saturn’s surface equatorial magnetic field is $21 \, \mu T$ and the magnetic moment is approximately $21000 \, nT R_s^3$ [Acuña & Ness, 1980; Smith, et al., 1980] meaning that Saturn’s surface magnetic field is weaker than Earth’s, but its magnetic moment is stronger.

Saturn is unusual in the Solar System due to the fact that the tilt between the kronographic and magnetic spin axes is less than $0.1^\circ$ [Burton et al., 2010], whereas at Earth and Jupiter the corresponding tilts are approximately $11^\circ$ and $10^\circ$, respectively. Such a small tilt is a challenge to some theories of the generation of a dipole magnetic field. Another defining feature is that, like at
Jupiter, the field orientation is the opposite to that of the Earth: Saturn’s dipole field is directed from north to south.

Observations from Pioneer, Voyager and Cassini have been used to construct magnetic field models. These models have confirmed that whilst the field is predominantly dipolar, quadrupole, octupole and higher terms are also present. The quadrupole term, in particular, corresponds to a shift in the axis of the dipole by 0.037 Rs towards the north pole, along the rotational axis of Saturn [Dougherty et al., 2005].

2.2.2 Solar wind conditions at Saturn

The characteristics of the continuous outflow of plasma from the Sun - the solar wind - vary with distance from the Sun. The wind is primarily composed of protons and electrons, with trace amounts of helium ions and heavier ions. At Earth, at 1 AU, solar wind speeds can vary between 300 km/s and 900 km/s, with a mean speed of 450 km/s and mean proton and electron number densities of about 6.6 cm$^{-3}$ and 7.1 cm$^{-3}$ respectively [Cohen et al., 2007]. The solar wind dynamic pressure can be calculated to be of the order of approximately 2 nPa. The average interplanetary magnetic field magnitude is about 5 nT, while the IMF spiral angle is about 45° at Earth [Parks, 1991; Richardson & Paularena, 1998]. The corresponding average values are different at Saturn. The IMF spiral angle is larger, about 85°, the mean solar wind speed is approximately 500 km/s [Jackman et al., 2008], the IMF is weaker (0.5 nT) and densities are an order of magnitude lower [Young et al., 2005].
2.2.3 **Saturn’s magnetosphere**

2.2.3.1 **The ring region**

A schematic of Saturn’s magnetosphere is shown in figure 16. There are four main regions of the magnetosphere: the ring region, the inner magnetosphere, the plasma sheet/middle magnetospheric region and the outer magnetosphere [Gombosi et al., 2009]. Inside of about 3 Rs a major plasma source is the rings. However, despite being a major plasma source, the rings are also a major sink of ionized particles: the lifetimes of ions is usually short; hence this region of the magnetosphere contains very little plasma. The dipole magnetic field configuration holds in this area of the magnetosphere.

![A schematic of Saturn’s magnetosphere showing relevant magnetic field structures, plasma areas and moon orbits. Courtesy of NASA/JPL.](image)
2.2.3.2 The inner magnetosphere

The inner magnetosphere extends roughly between 3 \( R_S \) and 6 \( R_S \) and is important because it contains the inner icy moons, the cold plasma torus and contains some of the densest plasma in the system. The plasma in the inner magnetosphere is mainly cool water group plasma, with temperatures from about 1 eV to a few tens of eV. Other plasma populations exist: particles with temperatures from tens to hundreds of keV have low intensities depending on whether or not recent injections have taken place. The radiation belts - protons and electrons with temperatures of 1 MeV and more - have a peak intensity in the inner magnetosphere.

In this region again the magnetic field is dipolar and the magnetic field and plasma are nearly corotating with the planet. The magnetic field and plasma will rotate with the planet as long as no other forces act upon them. Ions and neutrals collide in the ionosphere, momentum is transferred and ions are forced to move with the atmosphere. Due to adherence to the frozen in theorem, the magnetic field and the plasma associated with it are forced to move too. Field aligned currents transport the angular momentum up magnetic field lines, instigating the rotation of magnetospheric plasma with the planet [Gombosi, 1998].

In the inner magnetosphere there is a high count rate of high energy penetrating radiation, which can be detected by the Cassini Plasma Spectrometer (CAPS) and Magnetospheric Imaging Instrument (MIMI) onboard Cassini. These instruments are described in detail in chapter 3. These counts
can cause anomalous readings in the data but are easily identified inside of 4 Rs. There are methods for removing the instrumental signal due to penetrating radiation, explained in more detail in section 3.2.1.5, and once removed it is possible to more easily observe additional particle populations in the inner magnetosphere.

There are two thermal ion populations present: a proton population at 20 eV and a water group ion population at 300 eV. There is a predominantly cold electron population in the inner magnetosphere, but a hotter population is also observed after the removal of the penetrating radiation [Arridge et al., 2012]. Signatures of plasma injections from the outer magnetosphere into the inner magnetosphere are also seen. Electron injection events tend to persist more than ion events in this region because electron loss through processes such as Coulomb collisions is slower than ions lost through processes such as charge-exchange.

The centrifugal forces on the plasma cause the plasma to diffuse away from the planet, but momentum must be conserved so the azimuthal motion of the plasma slows down, stretching the frozen in field lines azimuthally. Rigid corotation breaks down inside Enceladus’s orbit at 3.25 Rs and the plasma begins to sub-corotate at that distance from Saturn [Wilson et al., 2008].

2.2.3.3 The middle magnetosphere

The middle magnetosphere, between 6 and 14 Rs, contains the extended plasma sheet, which is a region of plasma of hot and cold populations that contribute to the ring current. The ring current at Saturn is analogous to the
ring current at Earth, except it flows in the opposite sense due to the magnetic field being reversed at Saturn [Bunce et al., 2008; Carbary et al., 2010; Connerney et al., 1983]. The plasma in the middle magnetosphere has much lower densities than the plasma in the inner magnetosphere except for at the peak of the radiation belt [Roussos et al., 2008]. The neutral gas density in the middle magnetosphere decreases from the orbit of Enceladus outward. There is a peak in energetic neutral atoms at approximately 9 $R_S$ [Carbary et al., 2008a] and an increase in the fluxes of low energy electrons [Arridge, et al., 2012].

The magnetic field is no longer dipolar in this region due to current systems and equatorial plasma which act to decrease the local magnetic field strength.

### 2.2.3.4 The outer magnetosphere

The outer magnetosphere contains the magnetodisc, which is created due to the transport of neutrals and plasma from the inner magnetosphere. When new plasma is created, it is picked up and accelerated to corotation velocities. The interchange instability pushes the plasma outwards, taking the magnetic field lines with it, altering the dipole configuration into a disc-like geometry. The disc field is a signature of stress balance between centrifugal and magnetic forces. This disc has an associated plasma sheet which has a bowl-like configuration for most of the Saturnian year, due to the tilt of Saturn’s magnetic axis to the impinging solar wind, as shown in figure 17 [Arridge et al., 2008b; Carbary et al., 2008b].
As the magnetic field and spin axis of Saturn are aligned so closely, there is very little oscillation of the equatorial field and plasma in the north-south direction, in contrast to the case at Jupiter. However, because of the tilt of the spin axis relative to the solar wind there is usually an observed displacement of the magnetic equator in a northward direction in relation to the spin equator. This appears to occur more in the outer magnetosphere, but on both the dayside and nightside of the planet, during southern summer conditions (as existed from SOI to equinox in 2009) [Cowley et al., 2006; Sergis et al., 2009].

The situation will have changed significantly by solstice in May 2017 when the Sun will have reached its maximum northern latitude.
2.2.4 **Electron distributions in the magnetosphere**

Another way of classifying regions within the magnetosphere is by the different electron distributions contained within it. The magnetosphere can be divided into three regions based on the characteristics of the electrons: the inner dense plasma torus, the extended plasma sheet, and the hot outer region, with boundaries between them at around 9 $R_S$ and 14 $R_S$ [Schippers et al., 2008]. Up to 9 $R_S$, energies are observed to be between 0.1 keV and 10 keV, increasing so that maximum energies are found to be at 9 $R_S$ [Schippers, et al., 2008]. Plasma beta varies from near 1 between $L = 8$ and 14 to more variable outside of $L = 15$ [Sergis et al., 2007]. There is a local time asymmetry, as on the nightside the intensity of electrons increases by up to two orders of magnitude.

For higher energy electrons, Paranicas et al. [2010] show that at the inner plasma torus densities increase with decreasing radial distance but temperatures decrease. Energies between 41 keV and 60 keV show peak fluxes between 7 $R_S$ and 9 $R_S$, coincident with the orbits of the moons Dione and Rhea, with minimum temperatures around the orbit of Dione, as shown in figure 18. It is believed this is significant because electrons with energies of approximately 50 keV orbit Saturn close to corotation speeds at this $L$ shell. There is also a peak in low energy electron fluxes about $L = 4$, probably due to the cryovolcanism of Enceladus [Paranicas, et al., 2010; Smith, et al., 2010]. Carbary et al. [2009] studied energetic electron fluxes between 100 keV and 485 keV and found a lower energy electron belt at the orbit of Mimas, and another between the orbits of Dione and Rhea. A local time asymmetry was
also noted, with intensities on the dayside a few magnitudes lower than on the nightside, concurring with the work by Paranicas et al. [2010].

![Intensity of 41 – 60 keV electrons with equatorial pitch angles between 50 and 130. Data were gathered between 2004 and 2010.](image)

From [Paranicas, et al., 2010]

### 2.3 Magnetospheric dynamics

There are many influences on the magnetosphere that affect the plasma dynamics, such as sources and sinks of plasma and the way in which the plasma is transported. Overall, the nature of the dynamics of Saturn’s magnetosphere lies somewhere between that of Earth and Jupiter’s magnetospheres. Saturn’s magnetosphere is dominated by internal plasma sources, corotation and mass loading like at Jupiter, but because Saturn’s magnetic field is much weaker than
Jupiter's it cannot create a large magnetodisc, as there is not enough plasma in
the inner magnetosphere to significantly stretch the field configuration. This
implies that Saturn's magnetosphere is Earth-like in several respects from the
point of view that it is influenced by processes such as reconnection and the
presence of the Dungey cycle [Cowley & Bunce, 2003].

2.3.1 **INFLUENCES ON SATURN’S MAGNETOSPHERE, SKR AND ROTATION PERIOD**

Saturn emits strong radio signals in a frequency band called Saturn Kilometric
Radiation (SKR). The emission is between 10 and 1300 kHz and has been
observed as both narrow band and diffuse emissions [Zarka & Kurth, 2005]. At
present it is not clear why this radio signature is observed, but it appears to
vary depending on factors such as the rotation phase of the planet and the solar
wind pressure. It is thought to be produced when electrons move along
magnetic field lines associated with the auroral regions of Saturn [Kurth et al.,
2009]. Radio emissions from a planet are often used to calculate internal
planetary rotation periods, particularly for giant planets without a solid surface
as the electrons that are thought to create the SKR are controlled by the
magnetic field, which links the electrons to the planetary interior [Zarka et al.,
2007]. This has not been a viable method for Saturn because the SKR period
appears to be modulated on timescales as long as years. In the past few years it
has been noted that the SKR has different periods in the northern and southern
hemispheres, 10.6 hours and 10.8 hours respectively [Gurnett et al., 2009], so it
is impossible to extrapolate a planetary rotation period from the SKR at this
time. The Saturn Longitude Systems (SLS*) have been formulated to take into
Chapter 2: Saturn’s magnetosphere

account this modulation [Kurth et al., 2008]. The SLS systems are locked to the period of the SKR and are used to organise magnetospheric phenomena in an often useful way.

The precise value for the rotation period is proving to be elusive as the observed radio period appears to have altered between the Pioneer and Voyager missions and the Cassini mission; earlier missions measured a saturnian day to be 10 hours and 39 minutes, but Cassini has measured between 10 hours 32 minutes and 10 hours 47 minutes [Giampieri et al., 2006] and this value is still under debate. At present there are four Saturn Longitude Systems (SLS 1-4) for which the first has a period of 10h 39m 24 ±7s and is based on Voyager measurements of the Saturn Kilometric Radiation (SKR) [Kaiser et al., 1980]. The others are based on Cassini measurements of the SKR, [Anderson & Schubert, 2007; Gurnett et al., 2007; Kurth et al., 2007; Kurth, et al., 2008] and the latest published values are 10.6h in the northern auroral region and 10.8h in the southern auroral region [Gurnett et al., 2011]. The reason behind the difference is a topic of huge interest at present, but is outside the scope of this thesis. The relatively short length of a saturnian day makes Saturn a relatively fast-rotating planet which affects the dynamics of its vast magnetosphere. The fast rotation rate induces centrifugal forces that cause the equatorial region of the planet’s atmosphere to be stretched and bulged, and the polar regions to flatten. The inner magnetosphere is dominated by this fast rotation and exhibits rigid corotation with the planet. The Vasyliunas cycle is more prevalent in Saturn’s inner and middle magnetosphere because of the fast rotation and centrifugal forces, but in the outer magnetosphere the Dungey cycle takes over.
2.3.2 Sources and Sinks of Plasma

The rings and moons are important, not only as bodies in their own right, but also as sources and sinks of plasma within the magnetosphere, directly affecting the kronian magnetospheric dynamics. The rings are made primarily of water ice which, through processes such as sputtering, develop a neutral gas atmosphere which can be ionised by solar ultraviolet radiation; thus the ring ionosphere is an important source of plasma to the magnetosphere [Poulet & Cuzzi, 2002; Tokar et al., 2005; Waite et al., 2005].

Enceladus has been recently found to be a source of plasma in the kronian system, releasing between 200 kg and 1600 kg of neutrals such as water vapour into the magnetosphere per second [Saur et al., 2008]. The neutrals are rapidly ionised and picked up, adding to the corotating plasma in the system. The overall plasma output of Enceladus is an order of magnitude less than that of Jupiter's moon Io but enough for Enceladus to be the primary magnetospheric plasma source, and the main source of E-ring particles. The mass loading of plasma due to Enceladus and the barrier the plume creates to the plasma flow deforms the magnetic field lines so they drape in the south polar region of the moon. This is shown in figure 19.
The other icy moons are also plasma sinks, creating absorption signatures as plasma is absorbed by their surfaces. These are discussed in more detail in chapter 6.

2.3.3 **Plasma Transport in the Magnetosphere**

A significant amount of the plasma transport at Saturn is thought to be via interchange instabilities, similar to processes at Jupiter, causing cold, plasma rich flux tubes from the inner magnetosphere to interchange with flux tubes containing tenuous, hot plasma from the outer magnetosphere, discussed in more detail in chapter 5 and in, for example Southwood and Kivelson [1987].
This process is governed by centrifugal forces exerted by the plasma on the magnetic field. The cold plasma can be removed via reconnection in the magnetotail, forming plasmoids that move down tail and escape, or through being lost down field lines into the ionosphere. Recent studies have shown that it is still unclear as to how the total extent of solar wind energy input into Saturn’s magnetosphere via reconnection at the magnetopause compares to Earth (and other planets). Current understanding of the reconnection phenomenon suggests that the local conditions required to promote magnetopause reconnection at Saturn are different from Earth. It is possible that a low-plasma beta is required in the magnetosheath for reconnection to occur and thus magnetic reconnection between the solar wind and the kronian magnetosphere is not necessarily Earth-like [Masters et al., 2012]. Saturn’s largest moon Titan also appears to have an effect on substorm occurrence [Russell et al., 2008].

2.4 Other features of Saturn’s magnetosphere

2.4.1 Aurora

The nature of auroral creation processes at Saturn has aspects common to analogous processes at both Jupiter and Earth. Jupiter has significant polar aurora driven by outer magnetosphere processes and interactions with the solar wind. At Jupiter, the main ovals are caused by the abrupt breakdown of corotation of the plasma in the outer magnetosphere. This generates field-aligned currents which carry particles from the magnetosphere into the atmosphere. Aurorae on Jupiter are also associated with the magnetic footprints of the moons Io, Ganymede and Europa. Magnetic footprints are
caused by an electrodynamic interaction between the planetary magnetic field and the plasma from the moon and are a signature of field aligned currents connecting the two. The plasma flowing past the moon obstacle triggers Alfvén waves, which establish the auroral current systems.

Saturn has bright auroral ovals at the polar regions and it is thought that they are created when energetic electrons interact with atomic and molecular hydrogen in the upper atmosphere. The main auroral emission on Saturn is not as persistent as on Jupiter and is thought to be due to reconnection which drives currents up from the ionosphere, leading to precipitation of electrons in the atmosphere. The reconnection arises because of strong shear in rotational flow between regions of open and closed field. Aurorae on Earth are created due to solar wind processes [Cowley et al., 2008; Kivelson, 2005]. Saturn’s aurorae have been imaged using a joint campaign between Cassini instruments and the Hubble Space Telescope (HST). The continuous ovals have been observed in visible, infrared (in H$_3^+$) and ultraviolet (H$_2$ and H) wavelengths [Badman et al., 2011; Clarke et al., 2005; Kurth, et al., 2009; Melin et al., 2011; Nichols et al., 2010; Stallard et al., 2007].

First detected during the Voyager flybys [Clarke et al., 1981], observations placed emissions in both hemispheres near 80° latitude. More recent measurements from the HST and Cassini campaigns place the auroral oval centred on the spin axis with a mean southern latitude of 75° and northern latitude which varies between 70° and 80°. The northern oval is smaller in radius than the southern oval by approximately 1.5° [Nichols et al., 2009].
2.4.2 Oscillations

Magnetospheric periodic oscillations (also referred to as oscillations or periodicities) are related to the SKR and therefore to the aurora. These oscillations have been observed in the in situ data; in plasma data [Gurnett, et al., 2007], magnetic field data [Giampieri, et al., 2006], magnetopause and bow shock positions [Clarke et al., 2010] and auroral oval positions [Nichols et al., 2008]. The SKR appears be modulated in a strobe like manner; with the phase varying independently of the position of the observer. The other magnetospheric phenomena appear to rotate around the planet at the period of the SKR [Andrews et al., 2010]. There has been a suggestion that these periodicities are caused by asymmetric high energy plasma pressures from particles that are injected and drift around the planet, although this model cannot explain why there are different oscillations at the northern and southern hemispheres [Brandt et al., 2010].

2.4.3 Radiation belts

Saturn, like Earth, has radiation belts, but the belts at Saturn are weaker than those at Jupiter because many of the energetic particles are absorbed by the moons and the rings [André et al., 2008]. The most prominent radiation belt is situated between the A ring and the orbit of Enceladus, from 2.3 Rs to 3.5 Rs. The radiation belts consist of extremely energetic relativistic electrons and protons up to tens of MeV and some other ions [Gombosi, et al., 2009]. It is believed that the electrons in the radiation belt become energised as they are transported from the outer magnetosphere or solar wind by diffusion, and are
then adiabatically heated [Paranicas et al., 2008]. An energetic neutral atom image of the radiation belts is shown in figure 20.

Figure 20: MIMI data superposed onto a map of Saturn, showing energetic neutral atom emission from the main radiation belt and the inner radiation belt (labelled “new radiation belt” in the figure). The colours represent the intensity of the radiation, from blue increasing to red and the purple lines denote the magnetic field lines. The location of Titan does not have any relevance for the radiation belts in this diagram. From NASA/JPL.

There is a very small radiation belt near the D ring, very close in to the planet. It is believed that this belt is made up of particles that have been created by the cosmic ray albedo neutron decay (CRAND) process, similar to Earth’s proton belt [Krimigis et al., 2005]. Closer to Enceladus’s orbit the radiation belt particles are absorbed by plume material but the belt reintensifies beyond 6 Rs.
These particles also contribute a small amount to the ring current. The radiation belts are weaker than Jupiter’s but are still able to weather the surfaces of the icy moons, liberating water and oxygen through sputtering processes [Paranicas et al., 2008]. There is also evidence of transient radiation belts between the orbits of the moons Tethys and Dione [Roussos, et al., 2008; Roussos et al., 2011].

2.4.4 Ring current

The presence of Saturn’s ring current was inferred from magnetic field data measured during the Voyager missions, and confirmed using data from the particle instruments when it was found to flow from west to east, in the opposite sense to that at Earth [Krimigis et al., 1983]. Plasma undergoing magnetic gradient and curvature drift motion in the equatorial plane produces the ring current, situated between 6 Rs and 12-22 Rs depending on the magnetopause location. The strength of the ring current varies between 8 MA when the magnetopause is near minimum location and 17 MA when the magnetopause is located further out [Bunce et al., 2007].

The ring current generates a magnetic field which is northward at the inner edge and southward at the outer edge, and this field can act to decrease and increase the local planetary magnetic field respectively.
The ring current also affects the shape of the magnetic field as it can act to expand the equatorial field lines outwards away from the planet. This is due to the increase of field magnitude at the outer edge of the ring current which is in opposition to the local fields above and below the equatorial plane. An ‘image’ of the ring current is shown in figure 21.

![Cassini/MIMI Ion Neutral Camera (INCA) map of the ring current from the northern hemisphere. Saturn is at the centre and the dotted lines represent the orbits of Rhea and Titan. This false colour image shows the intensity of the energetic neutral atoms emitted from the ring current due to charge exchange. During this process, energetic ions gain an electron and become neutral, thus INCA can record the intensity of the neutral atoms as a reflection of how many ions are undergoing charge exchange. Red is the highest intensity.](From NASA/JPL/JHUAPL.)
2.5 Saturn’s Icy Moons

When Cassini went into orbit in 2004 it was known that Saturn had over 20 moons, now we know it has over 60. The moons vary in size, density, shape, orbital plane and composition.

Saturn’s largest moon, Titan, is larger than the planet Mercury and has its own atmosphere, and many other moons are interesting in their own right. 24 moons have prograde, mostly equatorial orbits, while 38 are irregular satellites, some with retrograde orbits and some with highly inclined orbits.

The inner icy moons are the ones we concentrate on in this thesis. These include Mimas, Enceladus, Tethys, Dione and Rhea. These moons are situated between 2.3 and 9 Rs and all have equatorial orbits closely aligned with Saturn’s equatorial plane. The positions of the moons’ orbits can be seen in figure 14.

As the surfaces of these moons primarily consist of ices, they can be assumed to be perfect absorbers of energetic particles. Enceladus is a special case because the plume also absorbs particles.

Enceladus’s orbit is situated at 3.95 Rs and its radius is only 1/230 that of Saturn’s, but it is the most reflective body in the Solar System due to the fresh icy surface, giving the moon an albedo of 0.99 [Verbiscer et al., 2007].

Enceladus’s activity was discovered in 2005 after a series of close flybys in which magnetic field and plasma data revealed that, at the south pole of Enceladus, there is a plume which is ejecting water vapour, gas, ice granules
and dust into the Saturn system [Dougherty, et al., 2006; Hansen et al., 2006; Jones et al., 2006; Porco et al., 2006; Tokar et al., 2006; Waite et al., 2006].

Currently there are multiple theories for the driver behind the plume processes ranging from tidal heating to the ammonia in the plume acting as an “anti-freeze” lowering the melting point of any sub-surface ice [Smith, et al., 2010]. Evidence of liquid water at Enceladus implies a possible liquid water sub-surface ocean at the south pole although alternative theories do exist, e.g. based on clathrate-driven jets [Fortes, 2007]. This makes Enceladus an important candidate for future astrobiological missions. It has also been shown that micron-sized water ice grains from Enceladus’s plume are the primary source of the tenuous and diffuse E ring of Saturn.

The plume stems from fissures in the surface ice at the south pole, termed “tiger stripes” [Porco, et al., 2006], and the plume is the source of most of the water in Saturn’s magnetosphere. The plume material plays a significant role in plasma production in Saturn’s magnetosphere, as the plume material forms a toroidal neutral cloud of water between 2 and 10 Rs, with a density peak at Enceladus’s orbit [Smith, et al., 2010]. The ionisation of these neutrals by electron impact and charge exchange creates a significant amount of plasma that is picked up by the magnetic field and then corotates with the ambient magnetospheric plasma [Pontius & Hill, 2006].
2.6 Saturn-magnetosphere-icy moon interactions

Energetic electrons (with energies greater than 1 MeV at the distance of Enceladus from Saturn – [Jones, et al., 2006]) gradient and curvature drift in the opposite sense to the direction of corotation and of the moon’s orbital motion. This means that electrons encounter the icy moons from the face that leads the direction of motion, the leading edge. Whilst energetic electrons travel against corotation, low energy electrons and ions travel with the direction of corotation and of the moon’s orbital motion. This means that the cold plasma bombards the face that trails the direction of motion, the trailing hemisphere of a moon.

The direction of motion of the drifting electrons reverses at a transitional energy, which is dependent on L shell, pitch angle and the bulk velocity of the ambient plasma. Dropouts or wakes in the ambient plasma are created, called macro or microsignatures. Microsignatures are local interactions between moons and the surrounding plasma, creating a temporary depletion in the count rates of particles at a spacecraft crossing these features. The magnitudes of these dropouts are dependent on the longitudinal separation between the moon and the spacecraft. Macrosignatures are found between 2 and 7 Rs and are observed as dropouts in energetic particle intensities along moon L shells. These are permanent features and remain regardless of latitude or local time. Microsignatures will be discussed in greater detail in chapter 6.

If a moon has little electrical conductivity it will not influence any electric current significantly and will absorb most impinging local plasma. This means
an empty wake is formed, which is the case at Rhea and Tethys. This type of moon is called a simple plasma absorber, as is the Earth’s moon in its interaction with the solar wind. In an empty wake, because the magnetic field is frozen into the plasma, the field strength increases in the centre of the wake as the plasma flow moves to infill the wake.

Moons with larger conductivity do affect the electric current. Currents can flow through the moon so that a $\mathbf{J} \times \mathbf{B}$ force is exerted on the plasma. Currents such as the plasma pick up current and Pedersen currents at Enceladus are induced, providing the $\mathbf{J} \times \mathbf{B}$ force that accelerates and diverts the plasma around the moon. This leads to mass loading and hence a pile up of magnetic field lines which drape around the moon, at the apex of a wedge shaped structure called an Alfvén wing, as shown in figure 22. The Alfvén wing current system enhances the magnetic field upstream of the moon and reduces the magnetic field behind it [Khurana et al., 2007].
The surfaces of the icy moons can become charged by a combination of a photoelectron current, electron and ion currents and secondary electron currents. These currents can lead to negative surface potentials of the moons, up to values as high as -100 V [Roussos et al., 2010]. These high surface potentials can lead to electrostatic acceleration of dust grains and act as a driver of dust transport across moon surfaces. This process could also be a source of dust in the Saturn environment if the dust velocity can exceed the moon escape velocity. Another process that could occur due to surface charging

Figure 22: Cartoon showing how a magnetic field can be perturbed by a moon into an Alfvén wing configuration. From [Southwood et al., 1980].
is the repulsion of electrons away from the surface of the moon. This is discussed more in chapter 6.

### 2.7 Thesis overview

The work in this thesis utilises data from the Cassini Plasma Spectrometer’s electron spectrometer (CAPS-ELS) and other Cassini instruments. The following chapter describes these instruments in greater detail.

The scientific analysis throughout this thesis covers three main topics of interest in the kronian magnetosphere. The first (chapter 4) addresses the size and shape of the kronian magnetopause by establishing a new model [Kanani et al., 2010], one which has already proven useful for the entire Saturn magnetospheric community. The new model has already been used in a number of further studies and has been referenced therein. We developed the new pressure balance model using multi-instrument data analysis, building on past models and including new features. It has been shown that the model has improved on previous models due to the inclusion of the suprathermal plasma and variable static pressures in the pressure balance equation providing more realistic results.

The second study (chapter 5) concerns flux tube interchange and injection events in Saturn’s inner magnetosphere. We present a new survey of very young and large scale injection events observed particularly by the CAPS instrument. Surveys have been carried out in the past but our new survey seeks to use a larger dataset and a wider array of instruments.
Analyses were performed of each event, examining CAPS-ELS and IMS (ion mass spectrometer) data, magnetometer data from the MAG instrument, higher energy electron data from the Cassini Magnetospheric Imaging Instrument Low Energy Magnetospheric Measurement System (MIMI-LEMMS) instrument where possible, and data from the Radio and Plasma Wave Science (RPWS) instrument where possible. The primary aim of the detailed analysis was to quantify whether each event was made up of inward or outward flowing flux tubes. The successful determination of these radial flow directions would be a useful extension of the observational evidence concerning these events, for example, in terms of establishing plasma circulation patterns in the kronian magnetosphere. We seek to test previous interpretations of these events and hope to show a method with which the radial plasma flow direction of interchanging flux tubes can be determined. If it is possible to determine the flow direction of the event we then believe it will then be possible to determine the minimum velocity of the travelling flux tube.

We also seek to investigate any L shell or latitudinal dependence and pitch angle distributions in order to find out what butterfly distributions can tell us about the direction of flow of the injection event.

The third topic (chapter 6) concerns low energy electron enhancements associated with Saturn’s moon Enceladus. During an investigation of close flybys of Enceladus, discrete, short duration enhancements were found in the low energy electron plasma. We present the new features seen in the Enceladus L shell region of the kronian magnetosphere. The data from these new features
has been statistically surveyed and possible creation mechanisms are discussed.

These topics are all significant in their implications for the interactions, influences on, and dynamics of Saturn’s magnetosphere. One provides the size and shape of an important boundary to the magnetosphere hence is crucial in investigating the magnetosphere as a whole, one gives a diagnostic for plasma transport within the magnetosphere - something directly important for the dynamics of the system, and the third provides an insight into the sources and sinks of plasma in the magnetosphere and processes therein. Finally, a summary of the thesis, its conclusions and future work that could be pursued are outlined in the final chapter, chapter 7.
CHAPTER 3  INSTRUMENTATION AND AN INTRODUCTION TO THE DATASET

“Just call me the computer whisperer.”

Willow, BTVS, episode 5.1.

The scientific data presented in this thesis have all been gleaned from instruments on board the Cassini spacecraft. The projects in the following chapters have been multi-instrument studies, in particular the magnetopause model project. The primary instrument of use for this thesis has been the Cassini Plasma Spectrometer (CAPS) electron spectrometer (ELS), but the ion mass spectrometer (IMS), magnetometer (MAG), high energy particle detectors and radio wave detectors were also used. This chapter gives an overview of these instruments and their parent mission. The majority of the information has been gleaned from the relevant instrument papers [Dougherty et al., 2004; Gurnett et al., 2004; Krimigis et al., 2004; Young et al., 2004], but other references are used where applicable.

3.1 Cassini orbiter and mission

The Cassini-Huygens mission is a joint NASA, ESA and ASI (Italian Space Agency) venture that was created in order to enhance our knowledge of the saturnian system post-Voyager. Saturn had never been visited by an orbiter, and Cassini-Huygens became a flagship mission that cost over $3 billion in the late 1990s. Primary mission objectives were to answer key questions about the planet, its atmosphere and weather, the magnetosphere, the interactions of the
moons and rings and to land the Huygens probe on Titan to learn more about the giant moon and its atmosphere.

The main spacecraft was named after Giovanni Cassini who discovered some of the kronian moons and observed the gap between the A and B rings, today named the Cassini division. The probe was named after Christiaan Huygens. Huygens used his telescope to study Saturn in further detail; proposing that the rings were actually one solid ring, as well as serendipitously discovering Titan.

![Figure 23: The trajectory of the Cassini spacecraft from launch in 1997 to arrival at Saturn in 2004, using four gravity assists. From NASA/JPL website.](image)

Cassini was launched in October 1997 from Cape Canaveral Air Force Station and, after a series of gravity assists from Earth (August 1999), Venus (April 1998 and June 1999) and Jupiter (December 2000), arrived at Saturn in 2004,
where it underwent Saturn orbit insertion (SOI) on July 1st of that year. The trajectory of the flight can be seen in figure 23. During Cassini’s time in interplanetary space it explored the magnetospheres of Earth and Jupiter and some aspects of the solar wind. The nominal mission lasted four years with the Huygens probe leaving the main spacecraft on December 25th 2004, landing on Titan on January 14th 2005. The Huygens probe measured the physical parameters of the atmosphere of Titan during its descent, imaged the surface and examined surface properties of the moon [Lebreton & Matson, 2002].

The planned four year mission, termed the primary mission, ended in 2008 but it was extended for two years, called the Cassini Equinox Mission because of the kronian equinox occurring in August 2009, and then was extended again until 2017. The second extended mission has been named the Cassini Solstice Mission because it will encompass kronian summer solstice in May 2017. In 2017 Cassini will be the first ever probe to witness northern hemisphere summer, which will be interesting in terms of the analysis of the seasonal effects, such as the role of possible changes in weather on Saturn and Titan during summer as opposed to during winter. The current end of mission plan in 2017 is to deorbit Cassini into the atmosphere of Saturn. By 2017 the spacecraft will have spent a total of 13 years orbiting Saturn; the longest continuous observation of a planet other than Earth by a single spacecraft. This long period of time allows the observation of the effects of changing solar activity on the magnetosphere of Saturn, as one solar magnetic cycle is about 11 years. At the end of the primary mission Cassini had orbited Saturn 75 times, during the Equinox mission there were a further 64 orbits and by the end of the Solstice mission there are plans for 155 more, allowing the
combination of many years of data over different areas of the magnetosphere and at different latitudes. Taking all this into account, the Cassini mission has resulted in the most detailed description of Saturn and its magnetosphere to date.

The Cassini-Huygens spacecraft is one of the largest planetary missions built, standing as tall as an up-ended school bus, 6.7 m high and 4 m wide. There are a total of 18 instruments on the Cassini spacecraft including six of those on the Huygens probe.
The Cassini spacecraft can be seen in figure 24 in pre-flight testing at NASA’s Jet Propulsion Laboratory, just under a year before launch.

The main bus is made up of sections stacked on top of each other, with the high gain antenna (HGA) bolted on top. The HGA is 4 m wide and its primary function is to support communication with Earth. There are two low gain antennas nearer the bottom of the bus, intended to use as emergency.
communications, or when the high gain antenna cannot be pointed at Earth. The spacecraft is too far from the Sun to use solar power effectively so it is powered by radioisotope thermoelectric generators (RTGs). The spacecraft is three axis stabilised. Thrusters and momentum wheels are used to maintain spacecraft attitude by exchanging angular momentum between the wheels and the spacecraft. A drawback of a three axis stabilised spacecraft is that its instruments have a restricted field of view; it is necessary to turn the whole spacecraft in order to orientate the correct instrument to what it is trying to observe, and when some instruments are well orientated others cannot be, so they must ‘take turns’.

The two main scientific instrument pallets are the fields and particles pallet (most important for the study of Saturn’s magnetosphere and plasma environment) and the remote sensing pallet. These are both roughly half way up the body of the spacecraft and the instruments that make up these pallets are considered in the next sections. Figure 25 shows the Cassini spacecraft with instruments and other parts labelled, although the orientation of the spacecraft in this figure means that the Huygens probe is not included.
3.2 Cassini Plasma Spectrometer (CAPS)

To answer some of the many questions about Saturn’s magnetosphere, Cassini required a suite of plasma instruments to make up CAPS [Young, et al., 2004].
CAPS consists of two ion instruments and one electron instrument and each was designed to address different scientific objectives. These goals were defined after the evaluation of results from previous missions that studied Saturn. The Voyager missions did not have complete coverage of electron and ion velocity distributions, in particular between 6 and 14 keV for electrons and 6 and 30 keV for ions, and this fact was taken into consideration when designing CAPS. The instruments are the ion beam spectrometer (IBS), the ion mass spectrometer (IMS) and the electron spectrometer (ELS). CAPS also has a data processing unit (DPU), high-voltage power supply and an actuator in its suite. CAPS can transmit data back to Earth at a maximum rate of 16 kilobits per second per day [Russell, 2004]. CAPS is situated on the fields and particles pallet, tucked into the underside in order to block emissions from the main engines and thrusters that could cause chemical contamination of the data. CAPS is also separated from the radioisotope thermoelectric generators as they are a source of penetrating radiation and away from anything that could lead to electrostatic charging. The placing of CAPS is shown in figure 25.
The ion and electron instruments are mounted on top of each other in order to get the same field of view, and compatible measurements, for both ions and electrons, as shown in figure 26. As mentioned, Cassini is a three axis stabilised spacecraft which means that, except when the spacecraft itself is turning, the only way to achieve a wide field of view is to rotate the instrument.

Figure 27 illustrates the instantaneous field of view for each CAPS instrument. CAPS is mounted on an actuating platform which is able to sweep through about 1° per second about X-Y, meaning that the CAPS instrument is capable of maximum field of view of ±104° parallel to the Z axis. A wide field of view is important because ideally CAPS would have a $4\pi$ steradian field of view in

Figure 26: The three CAPS instruments pre-flight. Taken from Young et al [2004].
order to calculate the full correct set of moments. There are some obscuration effects from other instruments, giving a restricted total range of motion from -80° to +104°. In spacecraft coordinates, the azimuthal coverage of CAPS is in the X-Y plane, pointing towards -Y at 0° actuation angle and the elevation angle is measured out of the X-Y plane (the ~Z direction is towards the high gain antenna). The coordinate systems used at Saturn are described in Appendix A.

![Diagram showing the field of view of the three CAPS instruments in spacecraft coordinates. From [Rymer et al., 2001]].(image)

Table 1 gives a CAPS sensor performance summary. Figure 28 shows a cross section of all three sensors in the CAPS suite with typical particle trajectories and field of view. Figure 29 shows the IMS field of view, demonstrating how other instruments and spacecraft components can obscure the field of view. The ELS and IMS fields of view are very similar.
The measurement technique for all three instruments is based on the knowledge of how charged particles interact with electrostatic fields. The IBS measures ion velocity distributions and is made up of two hemispherical plates, one nested inside the other. An electric field is applied across the plates, causing the ion trajectory to be bent towards the detectors. IBS measures energy per charge and arrival angle over an energy range of 1 eV to 50 keV and has very high angular and energy resolution. It was specifically designed to measure ion beams in the solar wind and directional ion fluxes in Titan’s ionosphere so it was not used for analysis in this thesis. The other two sensors

<table>
<thead>
<tr>
<th>Parameter</th>
<th>IMS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy/charge response</strong></td>
<td></td>
</tr>
<tr>
<td>Range (eV/e)</td>
<td>1–50,280</td>
</tr>
<tr>
<td>Resolution (ΔE/E)FWHM</td>
<td>0.17</td>
</tr>
<tr>
<td><strong>Angular response</strong></td>
<td></td>
</tr>
<tr>
<td>Elevation sectors (number)</td>
<td>8</td>
</tr>
<tr>
<td>Instantaneous FOV (AZ × EL)FWHM</td>
<td>8.3° × 160°</td>
</tr>
<tr>
<td>Angular resolution (AZ × EL)FWHM</td>
<td>8.3° × 20°</td>
</tr>
<tr>
<td><strong>Mass/charge response</strong></td>
<td></td>
</tr>
<tr>
<td>Range (amu/e)</td>
<td>1 ~ 400</td>
</tr>
<tr>
<td>Resolution (M/ΔM)FWHM</td>
<td>8</td>
</tr>
<tr>
<td>Energy-geometric factor*</td>
<td>5 × 10⁻³</td>
</tr>
<tr>
<td><strong>Temporal response</strong></td>
<td></td>
</tr>
<tr>
<td>Per sample (s)</td>
<td>6.25 × 10⁻²</td>
</tr>
<tr>
<td>Energy-elevation (s)</td>
<td>4.0</td>
</tr>
<tr>
<td>Energy-elevation-azimuth (s)</td>
<td>180</td>
</tr>
</tbody>
</table>

*Applies to total field-of-view and includes efficiency factors.

Table 1: CAPS sensor performance overview. From [Young, et al., 2004]
in the CAPS suite however are used, and hence are discussed in more detail in the next two sections.

Figure 28: Cross section of the CAPS suite shown in the X-Y plane in spacecraft coordinates. The dot dashed lines show the expected particle trajectories. The areas blocked out in cross-hatches contain sensor electronics. Shaded areas show each instrument’s field of view. From [Young, et al., 2004].

The CAPS suite was powered down on the 17\textsuperscript{th} June 2011 due to the suspicion that it was causing a short circuit to one of the RTGs. It was switched back on on the 16\textsuperscript{th} March 2012.
3.2.1 **Electron Spectrometer (ELS)**

3.2.1.1 **Operation**

The ELS is a hemispherical top hat electrostatic analyser which measures the flux of electrons as a function of energy per charge and arrival angle over an energy range of 0.58 eV to 28,250 eV. A schematic of ELS is shown in figure 30.
Electrons, and other particles, incident on the instrument enter through a baffle at the top of ELS. The baffle and a special black coating that covers most of the internal parts of the instrument work to stop particle scatter and sunlight by absorbing solar photons and photoelectrons. This allows electrons from only a particular direction to enter; these then pass through a narrow slit between the concentric hemispherical electrostatic analyser plates. The outer plate is grounded and the inner plate has a positive voltage, in order to create a potential difference between the plates. This allows electrons with specific energies and angles governed by the potential to have the correct trajectory to be detected. Other electrons will not be able to pass through the analyser as their trajectory will cause them to impact the edge of the analyser and be absorbed. In order to collect specific energy electrons, the voltage on the inner

Figure 30: Cross sectional diagram of the ELS analyser. From [Young, et al., 2004].
plate can be varied to change the potential difference across the plates. A cross section of a top hat electrostatic analyser with electron trajectories is shown in figure 31.

![Diagram of an electrostatic analyser with electron trajectories](image)

**Figure 31:** A cross sectional view of a top hat electrostatic analyser with various particle trajectories shown for electrons with different energies.

The $E$ denotes the direction of the electric field and the $V$ denotes the voltage applied across the plates.

If the electrons survive passage through the analyser they are then passed through two microchannel plates (MCPs) that are positioned at the end of the analyser. Each MCP has a semi annular shape, consisting of many glass microchannels. The two MCPs are in a stack with a small gap between them and a voltage applied across them. Each channel is a separate electron multiplier made from a resistive material and the electrons impact the walls of the
channel causing a cascade of secondary electrons. The number of electrons produced per original electron is called the *gain*.

The MCPs are slanted and arranged one on top of the other to create a chevron pair stack. This is done in order to stop electrons from just passing through the tube and make sure they impact the inside of the tube. This maximises the gain of the MCP. MCPs work by multiplying the number of incident particles or radiation but still retain the spatial resolution. MCPs’ performance is dependent on the coating that covers the glass channels, the chevron formation and the voltage applied across the MCP. The coating has a limited lifetime because it degrades, which also means the MCP and the instrument have a limited lifetime. To combat this, a gold coated copper spacer is placed between the MCPs and the MCP voltage is increased periodically. The spacer reduces the voltage for a specific gain, so higher gains can be obtained later in the mission as the voltage is stepped up.

The cascade of electrons is collected by an arc formation of eight anodes, each covering a region of the sky $20^\circ$ by $5^\circ$ wide, providing a total field of view of $160^\circ \times 5^\circ$. The anodes register the direction of arrival of the electrons onto the MCPs. The electron paths and field of view of the anodes is shown in figure 28. The maximum gain given by the MCPs is approximately $10^6$ electrons per anode per second.

As the potential on the analyser plates is varied, the energy of the incident electrons is varied. The analyser steps through 64 logarithmically spaced energy levels from the highest energy (bin 1) to the lowest energy (bin 63) over a period of 2 seconds (31.25ms per voltage step). The 64th bin is used as
time to return the voltage from the lowest to highest energy, called a ‘fly back’ step, during which no readings are recorded. This stepping creates the entire dataset over the energy range. ELS has an energy passband of $\Delta E/E = 0.17$, which is the energy resolution of the instrument, independent of the energy. The lower energy bands are more closely spaced which means the resolution at the lower energies is higher.

### 3.2.1.2 Data products

The electron events detected at the anodes are then read out by the instrument, with the data passing to the DPU for transmission and processing. The final data products are organised by time, into the A and B cycles. An A cycle consists of sixteen scans of the 64 energy bins (each scan takes 2 s and it takes 4 s to scan each anode), taking 32 seconds, which is defined as the given period for the ELS. A B cycle corresponds to eight A cycles. All the instruments take their timing from a clock on board the spacecraft to initiate actions and record time stamps at which the data are collected. The readings have to be accumulated over a given period, processed and compressed and formatted for telemetry purposes. Because all the instruments share a limited telemetry bandwidth it means ELS cannot always return data at its highest possible resolution mode. There are a variety of modes in which ELS can operate, which differ in the way the data are reduced and organised. The quality of the scientific information collected is balanced with the amount of data stored. Mode changes can affect the way the data are analysed as the resolution varies for different modes.
3.2.1.3 **Geometric Factor**

The raw electron counts are not a suitable quantity for a quantitative scientific analysis of the data, and the geometric factor, $G$, is required to calibrate the data. The units of $G$ are $m^2 \text{sr eV eV}^{-1}$ where $\text{sr}$ are steradians. $G$ is dependent on energy, arrival direction of the electrons, area of the sensors and the electron number density. The MCP efficiency is also taken into account [Linder et al., 1998]. The geometric factor for ELS was derived by simulations then ground calibration tests. In flight, the ELS also undergoes cross calibrations to ensure $G$ has not changed over time. If there is a discrepancy between $G$ measured during calibration and $G$ measured in flight, a correction factor is used to adjust $G$ accordingly [Lewis et al., 2010].

3.2.1.4 **Spacecraft Charging**

In space, when in a high plasma density environment, the spacecraft is exposed to large fluxes of electrons and ions. Solar irradiance can cause the spacecraft to emit photoelectrons and secondary electrons. Secondary electrons are also produced when plasma electrons impinge the surface of the spacecraft, emitting electrons with energies of a few tens of eV. There is a current balance that determines the spacecraft potential. When the current relationship given in equation 3.1 is in equilibrium the net current to the spacecraft is zero.

\[ I_i + I_e + I_{pe} + I_{se} = 0 \]
I_i and I_e are the ion and electron currents respectively, I_{pe} is the photoelectron current and I_{se} is the secondary electron current. The plasma environment and the location of the Sun in relation to the spacecraft are important in defining the way the balance is achieved.

Spacecraft photoelectrons are created when the spacecraft is in sunlight. Solar UV radiation is incident upon the spacecraft material, releasing photoelectrons. The energy of the photoelectrons depends on the material which the photons ionise; generally spacecraft photoelectrons have energies of a few eV as they are released from multi-layer insulation.

If the spacecraft is in a region where there is a tenuous plasma, or where the photoelectron term in equation 3.1 dominates (in sunlight) and the electron term cannot compensate, a positive potential is created, meaning the spacecraft becomes positively charged, which is the usual case for Cassini.

Photoelectrons and plasma electrons are attracted to the spacecraft when it is positively charged. Energetic photoelectrons can leave the spacecraft if their energy exceeds the spacecraft potential, but electrons lower than this energy are attracted to the spacecraft. This means a negatively charged cloud is formed around the spacecraft and the charge separation this causes creates a potential difference between the spacecraft and the surrounding plasma, which can affect the plasma properties.

The spacecraft can also become negatively charged, for example in a region of dense plasma or in an eclipse, because electrons become attached to the spacecraft at a higher rate than that at which photoelectrons are produced. A
negative charge is built up and external electrons can become decelerated or even repelled from the spacecraft.

Because the spacecraft potential can have such a significant effect on the ambient plasma and because the ELS analyser is sensitive to energies under 100 eV (because it is possible that the spacecraft potential level could reach -100 eV), being able to determine the value of the spacecraft potential is important in accurately measuring electron counts using ELS.

![Figure 32: Electron energy time spectrogram from the 14th July 2005. The black line indicates the maximum energy of photoelectrons during a period of positive spacecraft potential. From Lewis et al., [2010].](image)

Photoelectrons with energies higher than a given positive spacecraft potential are able to escape the spacecraft and are not detected. This means that
photoelectrons that are detected should have an energy equivalent to or less than the positive spacecraft potential. This also means that for a negative spacecraft potential, ambient low energy electrons are not detectable because they cannot overcome the spacecraft potential. If the spacecraft is positively charged the potential can be seen in the electron data but if the spacecraft is negatively charged the electron counts drop below the lowest energy level measurable by ELS and it is not possible to observe the entire electron population within the nominal ELS energy range. This is demonstrated in figure 32. If the negative spacecraft potential case occurs, it is necessary to use other instruments, such as the Radio and Plasma Wave Science instrument, to calculate the spacecraft potential. Electron densities can be calculated from upper hybrid frequencies then these densities are used to estimate spacecraft potential [Lewis, et al., 2010; McAndrews, 2007].

3.2.1.5 Penetrating radiation removal

Another factor affecting the measurement of electrons by ELS is high energy penetrating background radiation. When Cassini is in a region of MeV electrons, these particles can penetrate the instrument to cause electron signatures in the MCP regardless of the nominal observed energy, and are detected as a steady count level at all energies, varying as the spacecraft moves to regions of higher or lower MeV fluxes. Counts thought to be due to penetrating radiation can be subtracted from the data in order to better analyse the real plasma counts. At present the process for penetrating radiation removal is to take a measure of the counts in energy bands 50 to 54 for each anode, then remove those from
the entire data set for each anode. This method is good but it can remove real structure in the dataset, so often it is necessary to remove the penetrating radiation manually [Arridge et al., 2009]. A new method is being formulated, but was not implemented before the writing of this thesis.

### 3.2.1.6 Electron moments calculation

In order to calculate the electron density, temperature and other such parameters (collectively called ‘moments’) the particle distribution function should be integrated over three-dimensional velocity space. There is a general moment equation:

\[
M(x, t) = \int v^n f(v, x, t) \, d^3v
\]

3.2

where \( M \) is the moment, \( v \) is the velocity, \( n \) is the order and \( f \) is the distribution function in seven dimensions i.e. the phase space density.

The zeroth order moment gives number density, as shown in equation 3.3.

\[
n = \int f(v) \, d^3v
\]

3.3

The first order moment divided by the density, gives the bulk flow velocity, as shown in equation 3.4.

\[
\nu_b = \frac{1}{n} \int v f(v) \, d^3v
\]

3.4
The second order moment gives the stress tensor, which, in the plasma rest frame, is used to calculate the pressure tensor of the distribution, as shown in equation 3.5.

\[ P = m \int (v - v_b) \cdot (v - v_b) f(v) \, d^3v \]

3.5

From the pressure moment equation the temperature can also be defined. This is described in equation 3.6.

\[ T = \frac{m}{k_B n} \int (v - v_b) \cdot (v - v_b) f(v) \, d^3v \]

3.6

For CAPS-ELS it is assumed that the electron distribution is isotropic; it is not possible to know whether this is correct because the instrument only samples a limited section of the sky at a time.

Moments calculations can be performed in one dimension but three dimensions give more accurate results. This is because the one dimensional calculation assumes that the distribution function is a Maxwellian, but in reality the actual form of the distribution function is unknown.

The raw data are in units of count rate and must be converted into phase space density in order to carry out the moments calculations. This can be done using equation 3.7.

\[ f(v) = \frac{2N}{t_0 v^4 G(E)} \]

3.7
where \( N \) is counts, \( t_a \) is accumulation time minus dead time, \( v \) is the velocity of the electrons (from \( E=0.5mv^2 \) where \( E \) is the measurement energy) and \( G(E) \) is the geometric factor [Lewis et al., 2008].

### 3.2.2 Ion Mass Spectrometer (IMS)

IMS detects ions up to \( \sim 50 \) keV and can provide compositional information about the chemical species of ions present in Saturn's magnetosphere. The instrument measures positively charged atomic and molecular ions as a function of energy per charge, mass per charge and the angle of arrival.

IMS is similar to ELS in that it uses an electrostatic analyser to select particles of a chosen energy per charge but the shape of the analyser is toroidal not hemispherical. IMS also has a carbon-foil based time of flight (TOF) mass spectrometer with a linear electric field (LEF) timing region to measure mass per charge after energy per charge is selected. The TOF analyser is cylindrical and the LEF rings are placed around the outside of it. The LEF rings focus positively charged particles with energies < 16 keV so that they are detected by the LEF MCP. The trajectories of higher energy positive ions (> 16 keV), negative ions and neutrals are less focused in a straighter path to be detected by the straight through (ST) MCP. Figure 33 shows a schematic of the IMS.

The field of view is \( 160^\circ \times 12^\circ \), made up of eight anodes each observing \( 20^\circ \times 12^\circ \). The energy per charge is varied through 64 logarithmic energy values ranging from 1 eV to 50.28 keV over 4 seconds.

The electrostatic energy per charge analyser only allows ions of a specific energy per charge and direction of arrival to enter the instrument, and these
ions then pass on to the TOF analyser. The ions that exit the analyser are accelerated by -14.56 kV into one of eight carbon foils around the entrance of the TOF analyser. The ions pass through the acceleration field and gain enough velocity to penetrate the foils. As the ion exits the foil, secondary electrons are emitted and detected by the start MCP. At this time the TOF start signal commences and the direction of arrival of the ions is also measured. When the ions hit the end MCP at the end of the LEF rings the TOF stop signal is triggered. Anodes are placed under the start and LEF MCPs which collect the emitted electrons. These electron signals are then amplified and sent through a time-to-digital converter, which measures the interval between the start and stop MCP times.
For ions with an energy-charge ratio $< 15.5 \text{ keV/q}$ the ions are sufficiently slowed so their trajectories bend almost through 180° and they impact the LEF detector at the top of the time of flight analyser. For ions with $E/Q > 15.5 \text{ keV/q}$ their trajectory is not bent and, while they are slightly retarded, they are massive enough to continue through and hit the ST MCP. The simplest results are for an ion that doesn’t break up on impacting the foil; a single spectrum peak is produced from the TOF data giving the ion’s mass to charge ratio. IMS is not able to identify mass or charge independently so the mass per charge ratio is important. Identifying molecular species of two or more atoms is more
complicated. For a single species the timer will be stopped when the daughter particle hits the LEF or ST MCP. The time taken to hit the detector is then used, with other information, to identify the species. The time of flight peak corresponds to a specific mass/charge for a specific parent ion. For larger molecules that break up, the pieces can hit either or both detectors, making the process more complicated. Many peaks are obtained and each peak is identified using calibrated characteristics such as peak width and overall shape. The pattern of peaks from daughter particles and their relative abundances can be used to characterise parent particles. The data can also be used to provide ion bulk velocities if the instrument is pointing in the ion ram flow direction.

3.3 Magnetospheric Imaging Instrument (MIMI)

The MIMI suite of instruments measures neutrals and energetic ions and electrons. The suite gives in situ measurements of charge, composition and energy and it creates image maps of the arrival direction of magnetospheric neutrals at the spacecraft. There are three instruments in the suite that produce these data products [Krimigis, et al., 2004].

The Ion Neutral Camera (INCA) analyses the composition and direction of incident energetic neutral atoms ranging between 7 keV and 3 MeV per nucleon. These energetic atoms are created when energetic ions undergo charge exchange with the local neutral gas.

To measure electrons and ions there is the Low Energy Magnetospheric Measurement System (LEMMS) and the Charge Energy Mass Spectrometer (CHEMS). CHEMS measures the three dimensional distributions of ions over an
energy range of 3 to 220 keV per charge. It can measure species with masses from hydrogen to iron.

LEMMS measures three-dimensional distributions of ions and electrons between 20 keV and approximately 130 MeV, overlapping the top end of the CAPS energy ranges. This allows cross calibration of MIMI and CAPS. LEMMS is a two headed telescope with a low and a high energy end. The low energy end measures up to about 2 MeV and the high energy end measures higher than 2 MeV with good energy resolution. The typical time resolution for the energy channels is 5.375 seconds per data point, although this can be varied.

LEMMS is mounted on a turntable, rather than an actuator, theoretically allowing for a 360° field of view, thus a wide pitch angle coverage, when the spacecraft is in certain orientations with respect to the magnetic field. The turntable took 86s to complete one rotation, but it stopped working in February 2005, thus LEMMS is now in a fixed position.

A cross section of LEMMS is shown in figure 34. Lower energy ions and electrons enter the ‘low energy end’ of the telescope through a collimator. This contains a permanent magnet which causes the ions and electrons to separate. The electrons are deflected by the magnetic field and impact different detectors depending on their energy. Ions are less deflected thus impact a different set of detectors.

Higher energy electrons and ions are measured by the same method but impact different detectors. Between the high and low energy detectors there is a gold absorber to ensure that the high energy and low energy electrons do not mix. LEMMS particle trajectories are shown in figure 35.
Figure 34: Cross sectional diagram of the LEMMS instrument.

From [Krimigis, et al., 2004].

Figure 35: Simulations of particles’ trajectories at the low energy end of LEMMS. E and F denote electron detectors and A denotes an ion detector.

From [Krimigis, et al., 2004].
3.4 Magnetometer (MAG)

The MAG instrument measures the ambient magnetic field at the spacecraft. The instrument consists of two parts: a fluxgate magnetometer (FGM) and a scalar vector helium magnetometer (S/VHM). Both are on an 11m boom so that the spacecraft magnetic field doesn't significantly contaminate the measurements; the FGM is about half way along it and the S/VHM is at the end. The S/VHM failed in November 2005 so FGM data only are used for this thesis, hence only the FGM will be discussed here. For a more detailed introduction to the S/VHM please refer to the instrument paper by Dougherty et al. [2004].

MAG provides high sensitivity measurements over a wide range from less than 1nT to thousands of nT, depending on the location of Cassini in the magnetosphere (or solar wind). Having a dual magnetometer improved in-flight calibration and fulfilled the requirements of the mission, such as the ability to measure the magnetic field during Titan and Saturn encounters. With the dual technique it was possible to make vector (magnitude and direction) and high precision scalar (magnitude only) magnetic field measurements using the S/VHM and vector magnetic field measurements using the FGM.

The FGM has three single axis fluxgate sensors mounted perpendicular to each other onto a glass and ceramic block. The blocks are used because of their low thermal expansion coefficients, minimising misalignments of the sensors due to temperature variations. A fluxgate sensor has a primary, or drive, coil wrapped around a magnetically permeable ring, encased in a rectangular secondary, or sense, winding. The FGM is shown in figure 36.
An approximately 15 kHz square wave is applied on the drive coil which causes the ring core to cycle from fully magnetised to unmagnetised and so on, i.e. saturation. This induces an electric current to flow through the drive winding and half the core becomes magnetised in one sense, and the other in the opposite sense. If there is no external magnetic field, the two halves of the core will cycle through from maximum to minimum saturation at the same time. The fields cancel each other as they are the same strength but opposite orientation which means that there is no overall change in flux hence no induced potential difference. A schematic of a single fluxgate sensor is shown in figure 37.

Figure 36: A photograph of the MAG-FGM without its casing.

From [Dougherty, et al., 2004].
An external field this would affect the halves of the core in different ways. If half the core has a field opposite to that of the external field, the core field becomes weaker and it changes its cycle of magnetised and unmagnetised sooner than the other half of the core. The half of the core that has a field in the same sense as the external field finds its field becoming stronger, so takes longer to change cycles. This means the timing between cycle changes is not simultaneous, leading to the cores not being able to cancel each other out. A potential difference is induced in the sense winding, with an amplitude that is proportional to the strength of the external field, in the direction of the axis of sensitivity of the fluxgate sensor.

The work presented in this thesis uses MAG data with 1 second resolution where possible.
3.5 Radio and Plasma Wave Science (RPWS)

The RPWS instrument measures radio signals and plasma waves in Saturn’s magnetosphere. It is able to do this by measuring the electric and magnetic field, electron density and temperature close to the spacecraft. The instrument is made up of three orthogonal magnetic antennas, three nearly-orthogonal 10m electric antennas, a Langmuir probe and five receivers [Gurnett, et al., 2004].

The Langmuir probe is a metallic sphere that is charged and is able to measure electron temperature and density, provided that the electron density is high enough that the Debye length is less than 1m. The probe is on a 0.8 m boom starting from the position of the magnetic antennas. A voltage is applied to the probe so that the electrons in the local plasma generate a current. The relationship between the current and the voltage can be used to extrapolate density and temperature. A sweep of voltages is applied to the probe and the associated currents are measured. The Langmuir probe can be used in areas where densities are greater than $1 \times 10^7$ m$^{-3}$. If the probe is positively charged the current is directly proportional to the electron number density. The probe can become negatively charged in a high density region, in the same way that the spacecraft can become negatively charged in a high density region. This can induce a current flow which is used to determine the electron density. In a negatively charged regime it can be shown that the electron temperature is inversely proportional to the slope of the log of the current, which is useful because otherwise it can be very difficult to measure electron temperatures using other methods.
A problem of using a Langmuir probe is that spacecraft charging can alter the voltages although the amount by which it is offset can be measured and accounted for using the voltage-current characteristics of the probe.

The magnetic antennas are used to detect the magnetic element of the electromagnetic wave between 1 Hz and 12 kHz. The electric antennas are used to detect the electric fields between 1 Hz and 16 MHz. The reason there are three antennas of each type is so that direction finding and polarisation measurements can be performed.

The different instruments that make up the RPWS are not all on one pallet, they are dispersed about the spacecraft. The magnetic antennas are mounted on a boom near the high gain antenna, and aligned with the spacecraft axes. The electric antennas all point in different directions, their positions are shown in figure 38.
The RPWS measurements that are used in this thesis are upper hybrid wave data from the high frequency electric antenna, which, if the upper hybrid frequency can be identified, can be used to derive electron density when it cannot be derived from the ELS, for example during periods of negative spacecraft potential. The electron densities from RPWS can also be used for in-flight cross calibration with electron densities from ELS. The upper hybrid frequency is derived as shown in equation 3.8.
where $\omega_p$ is the electron plasma angular frequency (equation 3.9) and $\omega_c$ is the electron cyclotron angular frequency (equation 3.10).

$$\omega_p = \sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}}$$

3.9

$$\omega_c = \frac{eB}{m_e}$$

3.10

These equations are amalgamated, along with the equation $f=\omega/2\pi$ and the fact that $f_c = 2\pi B$ (where $f_c$ is in Hz and $B$ is in nT) to obtain the formula for the electron density in cm$^{-3}$, as shown in equation 3.11.

$$n_e = \frac{(f_{\text{UH}}^2 - f_c^2)}{8980^2}$$

3.11

### 3.6 An overview of typical plasma observations in Saturn’s magnetosphere as viewed by CAPS

Figure 39 gives an overview of Saturn’s magnetosphere as viewed by ELS and IMS from the CAPS suite, during an inbound pass, periapsis and an outbound pass from SOI. Plot A shows the electron energy-time spectrogram for anode 5 and plot B shows the ion energy-time spectrogram for anode 1. The data is from SOI, covering the 30th of June and the 1st July 2004 (DOY 183 and 184) and
is organised to show an inbound pass, periapsis and the corresponding outbound pass. The inner magnetosphere data have had the penetrating background removed. Closest approach was at 02:39 UT on the 1st July but during the period between 00:00 UT and 03:25 UT the instrument was switched off due to a main engine burn, hence the black section in the middle of the data.

On a first glance at the data it is possible to see clear structures in both the electrons and the ions. There are four main areas of the magnetosphere: the outer magnetosphere containing hot, tenuous plasma which is predominantly made up of H\(^+\) (up to time A in the plot), the outer plasmasphere containing H\(^+\), O\(^+\) and W\(^+\) which are water group molecular ions such as OH\(^+\), H\(_2\)O\(^+\) and H\(_3\)O\(^+\).
which partially corotates (between A and B), the inner plasmasphere which
corotates more rigidly, containing mostly O\(^+\) and W\(^+\) (between B and C) and
finally a section of O\(^+\) and O\(_2\)\(^+\) over the A and B rings, the ring ionosphere (after
C) [Young, et al., 2005]. These regions are observed again outbound, marked by
the primed letters C' to A'. The inbound and outbound ion data are not
symmetrical, due to different spacecraft pointing inbound and outbound.

At the A and A’ boundaries, at 14.4 Rs inbound and 13.6 Rs outbound
respectively, an increase in density by an order of magnitude is observed. This
is thought to be the plasmapause. The plasmapause at Saturn is important
because outside it magnetic flux tubes tend to be quite empty, as their E\(\times\)B
drifs carry the tubes into the magnetotail where they lose mass. A corotating
ion with the same angular velocity as Saturn must have an energy of
0.5\(M(R/R_S)^2\) eV, where \(M\) is the mass in amu. This equation is used to calculate
the corotation profiles, superimposed onto figure 39 as blue curves. The upper
curve is for O\(^+\) and the lower curve is for H\(^+\). The density increase shows an
approximate corotation pattern with broad peaks at corotation energies of
protons and water group ions.

At approximately 9 Rs inbound and 7.6 Rs outbound, at B and B’ respectively, a
second boundary is crossed as the inner plasmasphere is entered. The plasma
motion becomes more obviously corotating but the bulk of the flow appears at
energies higher than calculated. The reason for this is possibly because the
measured ion energy is the sum of the corotation energy and ion thermal
energy.
In the inner plasmasphere there are two populations of electrons, fit best by a bi-Maxwellian velocity distribution. There is a colder component between approximately 3 and 30 eV with increasing density for decreasing temperature and radial distance. There is a hotter component between approximately 100 to 1000 eV which has increasing temperature for decreasing density and radial distance.

Inside 6.3 Rs inbound and 5.9 Rs outbound the cold electron energies are bounded by the proton corotation energy, a feature which is yet to be explained [Young, et al., 2005]. Between 4.4 Rs and 10 Rs in this data (but observed closer in and further out later on in this thesis) signatures of plasma injections from the outer magnetosphere into the inner magnetosphere are seen. The time resolution of figure 39 is not sufficient to be able to see these injections as most injections are short lived, but they are discussed in greater detail in chapter 5.

Between A and B the spacecraft potential goes positive; this can be identified by the high counts of low energy electrons under approximately 5 eV, in red in figure 39. These are spacecraft photoelectrons caused by the spacecraft being in sunlight where the plasma is too tenuous to drive the potential negative. In the other regions the spacecraft has negative spacecraft potential, charged to approximately a few volts negative, due to the dense plasma particularly within about 9 Rs. The problem with a negative spacecraft potential is that ELS is not able to accurately measure the entire electron energy spectra, so it is hard to calculate electron moments when low energy electron are not measured and the spacecraft potential is unknown.
CHAPTER 4  A NEW FORM OF SATURN’S MAGNETOPAUSE

“Look how teeny Mercury is compared to, like, Saturn...”

Xander, BTVS, episode 5.9.

An introduction to planetary magnetopauses has been made in chapter 1 but this chapter discusses in greater detail the magnetopause of Saturn and how its form is dependent on a pressure balance between the solar wind and the magnetosphere. Much of the work presented in this chapter has been published in Kanani et al. [2010].

Saturn’s magnetopause was detected for the first time in 1979 by Pioneer 11, then by Voyager 1 in 1980 and Voyager 2 in 1981 [Russell & Luhmann, 1997]. All of the observations by these spacecraft were useful in the study of the magnetopause, but the orbital nature of Cassini’s mission has a greater insight into this magnetic and plasma boundary. Cassini has undertaken hundreds of crossings of the magnetopause between the kronian magnetic field and the shocked solar wind and, due to the multi-instrument aspect of the spacecraft and the long duration, new studies have presented magnetic latitude and local time data that are broader and more representative than “snapshots” provided by flyby encounters.

As mentioned in chapter 2, Saturn has many sources of plasma, including its rings, the solar wind, the ionosphere and its moons. The Cassini spacecraft has confirmed that the plasma environment is mainly composed of water-based
molecular and atomic ions and electrons [Young, et al., 2004]. Three fundamentally different regions of plasma have been identified and discussed in chapter 3: the hot outer magnetosphere, the extended plasma sheet and the inner plasma torus. The hot outer region of the magnetosphere is where the suprathermal electrons reside, dominating the electron pressure and density, whereas the plasma sheet and torus have enhanced levels of cold plasma relative to the outer magnetosphere [Sittler Jr, et al., 1983]. In contrast to the terrestrial magnetosphere, these internal magnetospheric plasma sources introduce significant amounts of plasma into the system. These populations, when heated, contribute a hot plasma pressure component that plays an important role in determining the configuration of the magnetosphere and hence, the magnetopause. Periodic modulations of internal plasma pressures can lead to periodic modulations of the magnetopause boundary layer [Clarke et al., 2006].

The solar wind and interplanetary magnetic field (IMF) characteristics at approximately 9 AU are somewhat different from those at Earth. Solar wind proton number densities were measured by Cassini at Saturn to be in the range of 0.002 to 0.4 cm$^{-3}$ and flow velocities typically range between 400 and 600 km s$^{-1}$ [Crary et al., 2005]. The main component of pressure in the solar wind is the dynamic pressure, as stated in equation 4.1

$$D_p = \rho u_{SW}^2$$

where $D_p$ is the dynamic pressure, $\rho$ is the solar wind mass density and $u_{SW}$ is the solar wind velocity. As mentioned in chapter 1, the solar wind is primarily
composed of protons but also includes between 4% and 20% doubly ionized helium [Aellig et al., 2001]. This means that the exact solar wind pressure will be uncertain because Cassini is unable to directly measure the solar wind composition at the same time as measuring magnetospheric plasma pressures.

4.1 The pressure balance equation

The magnetopause can be considered as a surface where the total (particle and field) pressure inside the magnetosphere balances the total pressure in the magnetosheath. In reality these pressures will not be perfectly balanced and the magnetopause will be in constant motion. Increases in the solar wind dynamic pressure cause the magnetopause to contract, the magnetosphere to compress and the magnetic field strength at the magnetopause to increase. As a consequence of the increase in solar wind dynamic pressure, the magnetosphere exerts a greater outward pressure on the magnetosheath and reaches a new equilibrium magnetopause location, which is inward of the initial position, before the dynamic pressure increase. To a first order, one can consider the magnetopause to be a pressure balance surface and as a simple approximation of this equilibrium, the magnetic pressure inside the magnetosphere balances the dynamic pressure of the solar wind (equation 4.1). This pressure balance equation, applicable only at the subsolar point where forces are perpendicular to the magnetopause, is described in equation 4.2.

\[ \rho u_{SW}^2 = \frac{B^2}{2\mu_0} \]
Knowledge of \( B \) as a function of distance from the planet allows the construction of an expression for the standoff distance, \( R_0 \), of the subsolar magnetopause as a function of solar wind dynamic pressure.

For a pure dipole magnetic field, \( B \sim r^{-3} \), where \( r \) is the distance from the planet centre to the nose of the magnetopause, hence \( D_P \sim r^6 \) and the standoff distance can be written as \( R_0 \sim D_P^{-1/6} \). This relationship has been confirmed by modelling of the terrestrial magnetopause, for example [Shue et al., 1997]. However sometimes a magnetospheric fields may not be correctly modelled as a dipole with a fixed magnetic moment, but more accurately as a stretched configuration with a magnetic field strength that varies more slowly than \( r^{-3} \).

This type of magnetospheric configuration requires a smaller increase in \( D_P \) to compress the magnetosphere by a given change in \( R_0 \) than is required at Earth, and hence the \( R_0 \sim D_P^{1/6} \) power law has a somewhat larger exponent, i.e. larger magnitude.

Equation 4.3 exposes the relationship between \( R_0 \) and \( D_P \), where \( \alpha = 6 \) for a dipole and is smaller for a more stretched configuration, therefore \( \alpha \) can be considered a diagnostic of pressure balance and internal structure within the magnetosphere.

\[
R_0 = D_P^{-\frac{1}{6}}
\]
The pressure balance expression in equation 4.2 ignores thermal plasma pressure in the magnetosheath and magnetosphere. Equation 4.4 represents a pressure balance including these additional pressures.

\[ \rho u_{sw}^2 + P_0 = \frac{B^2}{2\mu_0} + P_{MS} \]

Equation 4.4 represents the balance between the pressure components of the solar wind plasma: the dynamic pressure and thermal static pressure \( P_0 \), with the pressure components inside the magnetosphere: the magnetic pressure and the internal particle pressures \( P_{MS} \).

The pressures external to the magnetosphere are actually pressures in the magnetosheath and to relate them to upstream (solar wind) conditions Bernoulli’s equation is used. Assuming an adiabatic flow between the upstream bow shock and the magnetopause stagnation point, the stagnation pressure can be related to the pressure at any point upstream along the same streamline [Walker & Russell, 1995].

\[ \frac{P_S}{P} = \left(1 + \frac{\gamma - 1}{2} M_S^2 \right)^\frac{\gamma}{(\gamma-1)} \]

Equation 4.5, where \( P_S \) is the stagnation pressure, \( P \) is the pressure at a point along the streamline, \( \gamma \) is the ratio of specific heats and \( M_S \) is the sonic Mach number \( (M_S = \frac{u}{\sqrt{\gamma}})^{0.5} \).
Using the Rankine-Hugoniot jump conditions to describe the changes experienced by the solar wind plasma crossing the bow shock, where the subscript SW refers to the solar wind, and combining these with the stagnation pressure equation, an equation relating the stagnation pressure to the solar wind thermal pressure is obtained:

\[
P_S = p_{SW} \left( \frac{(\gamma + 1)^{\gamma+1} \left( \frac{M_{SW}^2}{2} \right)}{2\gamma M_{SW}^2 - (\gamma - 1)} \right)^{[\gamma-1]-1}
\]

Therefore

\[
P_S = k \rho_{SW} u_{SW}^2
\]

where

\[
k = \left( \frac{\gamma + 1}{2} \right)^{\frac{\gamma+1}{\gamma-1}} \frac{1}{\gamma \left( \frac{\gamma - (\gamma - 1)}{2M_{SW}^2} \right)^{\frac{1}{\gamma-1}}}
\]

The coefficient \(k\) indicates by how much the pressure is diminished by the divergence of the flow and relates the solar wind dynamic pressure outside the bow shock, to the magnetospheric thermal pressure of the upstream solar wind inside the bow shock. For \(\gamma = 5/3\) and \(M_{SW} = \infty\), \(k=0.881\), which is a reasonable assumption for Saturn where the solar wind is a high Mach number regime. It is
thus necessary to include \( k \) in the pressure balance equation as it relates the
dynamic pressure in the solar wind to that in the magnetosheath.

Away from the stagnation point these pressures are modified by flaring of the
magnetopause, such that the plasma is no longer normally incident on the
magnetopause. The flaring angle \( \Psi \) is the angle between the solar wind
direction (along \(-X\) in KSM) and the local normal to the magnetopause, and is
0° for normal incidence (at the stagnation point). The flaring angle can be
found from the cross product of the magnetopause normal vector and the solar
wind direction. This is discussed in greater detail in section 4.2. Equation 4.9 is
based on equation 4.4 but includes the \( k \) factor and terms to account for the
flaring angle, so is valid everywhere on the magnetopause, not just at the
stagnation point.

\[
kD_p \cos^2 \Psi + P_0 = \frac{B^2}{2\mu_0} + P_{MS}
\]

At the subsolar point, \( \cos^2 \Psi \) is close to unity and the dynamic pressure
dominate in this pressure balance, but as \( \cos^2 \Psi \) decreases downstream the
thermal pressure becomes increasingly important. Petrinec and Russell [1997]
showed that using equation 4.9 and applying Bernoulli’s equation along a
streamline adjacent to the magnetopause resulted in imaginary flow velocities
in the subsolar region. Hence, a \( \sin^2 \Psi \) term is applied to the solar wind thermal
pressure term in equation 4.9 in order to force the flow velocity to be real in
the subsolar region. The equation without the \( \sin^2 \Psi \) provides reasonably
accurate results for high Mach number regimes but including the term is the
simplest formulation of the equation which satisfies both the demands of hydrodynamic flow at the stagnation point and the pressure balance demands downtail [Petrinec & Russell, 1997] as shown in equation 4.10.

\[ kD_p \cos^2 \Psi + P_0 \sin^2 \Psi = \frac{B^2}{2\mu_0} + P_{MS} \]

Studies of the terrestrial magnetopause are able to use monitors of the upstream solar wind conditions and hence the position of the magnetopause, as determined by particle and fields data from a spacecraft, can be directly related to the upstream solar wind measurements. For current outer planet missions there is no upstream monitor. Hence, a pressure balance method is used where equation 4.10 is applied to the measured interior magnetospheric plasma pressures and magnetic pressures, which allows for an estimation of the dynamic pressure at each crossing of the magnetopause. In equation 4.10 the dynamic pressure and flaring angle cannot be measured thus must be extrapolated.

Arridge et al. [2006] used this pressure balance technique to develop a new model for Saturn's magnetopause, but did not explicitly include the effects of internal particle pressure inside the magnetosphere. This chapter addresses the closing comments of Arridge et al. [2006], who realised that their model required further attention in order to account for the effect of internal plasma pressure on the pressure balance and the assumption of a constant static pressure. Energetic particle pressure data are now available and incorporating the internal pressures in Saturn’s magnetosphere into the pressure balance...
4.2 **Previous models**

There are many models that estimate the location of a planetary magnetopause, making feasible the investigation of its behaviour e.g. [Hendricks et al., 2005; Joy et al., 2002; Kawano et al., 1999; Sibeck et al., 1991]. It has been demonstrated that the power law relationship for a dipole magnetic field with a fixed magnetic moment [Shue, et al., 1997], is valid at Earth’s magnetopause as the plasma does not contribute significantly to the total pressure near the magnetopause and the ring current does not change significantly with system size [Bunce, et al., 2007]. For Jupiter the pressure balance method yields an exponent between -1/4 and -1/5 [Huddleston et al., 1998; Slavin et al., 1985] and for Saturn different studies have shown both a terrestrial-type -1/6 [Slavin, et al., 1985] and Jovian-like, -1/4 [Arridge, et al., 2006] response.

Three different types of pressure balance models of Saturn’s magnetopause have been developed: these types are given as examples in Slavin et al [1983], Maurice et al. [1996], Hansen et al. [2005] and Arridge et al. [2006]. The Slavin et al. 1985 model, herein referred to as S85, uses the pressure balance equation expressed in equation 4.9 to derive a relationship between the standoff distance and the dynamic pressure. S85 assumed k=1 and their model did not include internal plasma pressures so the $P_{MS}$ term in equation 4.9 was not used. S85 used the pressure balance method to infer $D_P$ and fitted a conic section to a
limited set of magnetopause crossings identified in Pioneer 11 and Voyager 1 and 2 data. S85 found $\alpha=6.1$, i.e. a magnetopause that scaled as a terrestrial magnetopause, but with increased flaring. However, the model was only valid between the subsolar point and the same distance tailward, between $X_{KSM} = 19$ and $-19 \text{ Rs}$. They argued that the increased flaring was due to the ratio between the solar wind dynamic and thermal pressures. Maurice et al. [1996] used a model for Saturn's magnetospheric magnetic field, in which the total magnetic field was derived using three different sources. The internal sources are the planetary dipole and the equatorial ring current and the external contribution is that of the interaction of the solar wind with the magnetosphere i.e. the field due to magnetopause currents. The magnetic field model was used to iteratively develop a new surface model for Saturn's magnetopause. They used the field model to calculate the magnetic field pressure inside the magnetosphere and a numerical technique to find the surface which was in pressure balance with the solar wind (via equation 4.2). Their model magnetopause was considerably less flared than the S85 model.

Hansen et al. [2005], herein referred to as H05, use the results of MHD simulations to investigate how the distance to the subsolar magnetopause varied with dynamic pressure. The model included internal plasma sources but the internal mass loading rate was adjusted so that the magnetopause was located where Cassini actually crossed the magnetopause on its approach and insertion orbit. The model implicitly includes the effects of internal plasma pressure but does not explicitly describe the multiple plasma populations that are present in Saturn's magnetosphere, and the large energy density in some of the energetic populations. H05 found that the magnetopause is less flared than
most previous models and is asymmetrical in the dawn-dusk meridian. The modelled magnetotail showed a hinge at 20RS due to the inclination of Saturn’s dipole to the solar wind, similar to that identified in Cassini observations [Arridge, et al., 2008a; Carbary, et al., 2008b]. To establish a power-law relationship between R₀ and D_p, H05 used a constant solar wind speed and varied D_p by controlling the solar wind plasma density. H05 found an α value of 5.2, between previously calculated values for Earth and Jupiter; corresponding to a magnetopause that is neither as rigid as the Earth’s nor as compressible as Jupiter’s.

Using the lack of upstream solar wind dynamic pressure measurements as a prompt, the authors of the Arridge et al. [2006] study (herein referred to as A06) presented a new technique for making a pressure dependent model. The model used data from Cassini and Voyagers 1 & 2, and the more elaborate form of the pressure balance equation as expressed in equation 4.10. For A06, k=0.881, which is valid in high solar wind Mach number regimes applicable for Saturn, as discussed in section 4.1.

The A06 model magnetopause is rotationally symmetrical about the X axis, and the polar coordinates of the magnetopause crossings can be calculated using equation 4.11. R is the distance from the planet to a point on the magnetopause and θ is the angle subtended at the planet by the X axis and a position vector to a point on the magnetopause.

\[ R = R_0 (\frac{2}{1 + \cos \theta})^k \]
The pressure-dependent size and shape of the magnetopause are set through equations 4.12 and 4.13 respectively.

\[ R_0 = a_1 D_p^{-a_2} \]  
\[ K = a_3 + a_4 D_p \]

Figure 40 demonstrates how varying \( R_0 \) and \( K \) affect the shape of the model magnetopause. \( R_0 \) affects the size and varying \( K \) changes how much the magnetopause flares. The dynamic pressure is used to create a model magnetopause, by fitting for modelled polar coordinates. The process uses equations 4.10, 4.11, 4.12 and 4.13. Dynamic pressures are inferred by iteratively fitting the magnetopause shape for coefficients \( a_i \). The process is described as a flow chart in figure 41.

A non-linear fitting process is used to find the model coefficients, minimising the root mean squared (RMS) divergence between modelled and observed magnetopause crossing locations (\( R \) and \( \theta \) values). At each iteration, \( \Psi \) and \( D_p \) are estimated then the RMS residual is found. Once the tolerance of this RMS deviation is reached, the fitting is complete. The tolerance is set manually or by the fitting routine used in the model (in this case, MPCURVEFIT in IDL). The iteration process is terminated when both the actual and predicted relative decrease in the sum of the squares are a specific value (the default in this routine was 1E-3). In fitting for the coefficients the model will converge successfully for inputted initial values of the coefficients. The algorithm employed is the non-linear fitting Levenberg-Marquadt routine that searches
for $a_i$ by minimising the RMS residual. The process converges so that estimated $D_P$ values are consistent with fitted model parameters.

Knowing model dynamic pressures for a particular crossing, it is possible to find the normal to the model magnetopause at that crossing. The normal vector can be found using equation 4.14, based on positions in the RTP ($r, \theta, \phi$) coordinate system. The RTP system is related to Cartesian coordinates by $\theta = \cos^{-1}(x/r)$ and $\phi = \tan^{-1}(z/y)$.

$$\vec{n} = \frac{\partial \vec{r}}{\partial \theta} \times \frac{\partial \vec{r}}{\partial \phi}$$

The components of these differentials are shown in equations 4.15, 4.16, 4.17 and 4.18.
\[
\frac{\partial \mathbf{r}}{\partial \theta} |_x = r \sin \theta \left( \frac{K \cos \theta}{1 + \cos \theta} - 1 \right)
\]

4.15

\[
\frac{\partial \mathbf{r}}{\partial \theta} |_y = r \cos \phi \left( \cos \theta + \frac{K \sin^2 \theta}{1 + \cos \theta} \right)
\]

4.16

\[
\frac{\partial \mathbf{r}}{\partial \theta} |_z = r \sin \phi \left( \cos \theta + \frac{K \sin^2 \theta}{1 + \cos \theta} \right)
\]

4.17

\[
\frac{\partial \mathbf{r}}{\partial \phi} = r \sin \theta \left( 0, -\sin \phi, \cos \phi \right)
\]

4.18

The dot product of equation 4.14 and the solar wind direction gives the flaring angle. Superficially it is possible to assume the direction of the solar wind is in the X direction so it is adequate to just take the X component of equation 4.14 in order to calculate the flaring angle.

A06 obtain \( \Psi \) directly from model normals; the model normal vector is calculated at each iteration, and \( \Psi \) is then computed from the scalar product of the model normal with the solar wind direction as mentioned previously. This means \( \Psi \) is model dependent. If a pressure balance is assumed the magnetopause geometry will affect the dynamic pressure. At each iteration \( D_P \) is also estimated as the coefficients \( a_i \) are evaluated, thus as the shape of the model changes, \( D_P \) and the flaring angle also change for current \( a_i \)s.
Chapter 4: Saturn’s magnetopause

The A06 model has a pressure response described by $\alpha = 4.3\pm0.4$ which represents a magnetosphere that is as compressible as the jovian system. However, the model does not take polar flattening into account due to its axisymmetry, which was forced upon the model due to a lack of high latitude crossings, a problem which also presents itself in the new model discussed in this chapter.

A06 also estimated the effects of a high plasma beta on the model magnetopause by doubling the magnetic pressures at equatorial locations and inferring a power law relationship from this. In a high beta regime, such as the one discovered in the kronian magnetosphere [Sergis, et al., 2007] A06 found a modelled power law of $\alpha=5.5\pm0.7$.

Figure 41: Flow diagram explaining the algorithm for fitting the new model magnetopause, as discussed in section 4.2.
4.3 Method
4.3.1 The new model

The new model uses the A06 numerical fitting algorithm for calculating $\Psi$ and $D_\rho$, as discussed in section 4.2. Changes were made to the A06 form of the pressure balance equation in order to address the issues highlighted previously. A constant static pressure ($P_0$) value for the upstream solar wind was replaced with a static pressure dependent on the dynamic pressure. During investigation of the new model, the results of the A06 pressure balance equation were compared to the numerical MHD simulations of H05. It became apparent that the static solar wind pressure component was too small in A06 because the A06 model magnetopause was considerably more flared than the H05 model magnetopause. The value of $P_0$ was varied and tested but larger values failed to correct the flaring, producing inconsistent results and often negative dynamic pressures. We recognised that $P_0$ varies with solar wind density and so the new model employs a solar wind density-dependent static pressure component. At constant temperature, the solar wind static pressure varies linearly with density since $P_0 = nk_B T$ where $n$ is the number density, $T$ is the temperature and $k_B$ is Boltzmann’s constant. Since the pressure balance equation is dependent on dynamic pressure and density, $P_0$ was thus expressed as a function of dynamic pressure assuming a fixed solar wind speed and Helium abundance. A factor of 1.16 was introduced into the static pressure term of the pressure balance equation (equation 4.19) to take into account an approximate 4% contribution of He$^{++}$ in the solar wind with a temperature equal to approximately four times the temperature of protons [Slavin, et al.,
1985]. Varying this factor did not have any significant effect on the fitted model parameters. The validity of assuming a fixed solar wind velocity was also tested by varying the velocity between 400 km/s and 600 km/s. It was found that different values of $u_{SW}$ did not notably change the best fit coefficients beyond their uncertainties.

The most significant modification to the A06 methodology was to include internal plasma pressures in the pressure balance equation in order to investigate the effects of high plasma beta regimes. Averages of high energy ion pressures were taken from the MIMI instrument for five minute intervals just inside the magnetopause at each crossing location [Sergis, et al., 2009]. Corresponding averages of low energy electron pressures, calculated using electron moments calculations as described in chapter 3, were taken from CAPS-ELS.

Low energy proton pressures were estimated using 20% of the low energy electron pressures given the assumption that total ion number density consists of ~20% protons. The proton temperature is observed to be approximately the same as the electron temperature. This assumption is based on the best available data at present; note that a possible contribution from water group ions has not been included in the CAPS energy range due to the fact that the water group pressure is included in the energetic pressure calculation. This cannot be improved at this time without a full multi-species pressure calculation from eV to keV ranges which accounts for the ion bulk velocity. Including these projected proton pressures generates results within the error margins, so the final results are stated without these estimates. The final
Chapter 4: Saturn’s magnetopause

Pressure balance equation is expressed in equation 4.19, where \( m_p \) is the proton mass. Knowing the magnetic pressure, the MIMI pressure, and the CAPS-ELS pressure, assuming values for \( T_{SW} \) and \( u_{SW} \), and inferring \( \Psi \) from the model normals makes it possible to calculate \( D_p \) from the pressure balance equation.

\[
k D_p \cos^2 \Psi + \frac{k_B T_{SW}}{1.16 m_p u_{SW}^2} D_p \sin^2 \Psi = \frac{B^2}{2\mu_0} + P_{MIMI} + P_{ELS}
\]

4.3.2 The data

The coordinate system used for the new model is the Kronocentric Solar Magnetospheric (KSM) system which is Saturn centred, where the X axis points towards the Sun, the X-Z plane contains Saturn’s centred magnetic dipole moment vector and the Y axis completes the right hand set, pointing duskwards.

The magnetopause crossings used in this study were identified using 1 second averaged CAPS-ELS data covering the period from before SOI in June 2004 until the end of January 2006. The spacecraft trajectories did not traverse the magnetopause for a significant amount of time after that date. In ELS data a magnetopause crossing can be identified as a boundary between higher density, lower temperature electrons in the magnetosheath and lower density, higher temperature electrons in the magnetosphere. A rotation in the magnetic field to a southward orientation is also seen when the boundary is crossed (unless the sheath field is also southward). However, variations in the plasma
data that are not apparent in the magnetic field data can also be identified as magnetopause crossings, as these are usually associated with the entry of the spacecraft into a boundary layer. Often, the magnetopause crossings involved a high magnetic shear and were very apparent in all datasets. In some cases the magnetopause crossing locations were not so clear in the magnetometer data; when this was the case, the plasma data were taken to be more reliable than the magnetic field data for the purpose of placing crossing locations. An example of typical magnetopause crossings are shown in figure 42.
Figure 42: Observations at the magnetopause obtained by CAPS-ELS and MAG. The top plot shows the energy-time spectrogram in units of electron count rate, the middle plot the magnetic field in KSM coordinates and the bottom plot the magnetic pressure from MAG data. MS denotes magnetosheath and MSP denotes magnetosphere. Three clear-cut magnetopause crossings are shown by the black dotted lines, at approximately 03.50 UT (outbound), 07.30 UT (inbound) and 13.40 UT (outbound).

Figure 42 illustrates three clear magnetopause crossings, two into the magnetosheath and one into the magnetosphere. These crossings are from 25 May 2005 when Cassini was slightly below the equatorial plane at ~32 Rs from Saturn on the dawn flank. Each crossing of the magnetopause is associated with a large rotation in the magnetic field and an increase in the magnetic field strength when crossing into the magnetosphere. In the plasma data upstream of the magnetopause, the colder, denser magnetosheath electron population is
apparent, whereas downstream of the boundary more energetic magnetospheric electrons are evident. Intense counts of electrons below around 10 eV are trapped spacecraft photoelectrons. In the magnetosheath the spacecraft potential is lower so the photoelectrons are cut off at the lower energies. This is expected because the magnetosheath is denser than the magnetosphere.
Figure 43: Magnetopause crossings used in this study. Panel (a) shows all the crossings in the KSM X-Y plane. The plot shows most crossings are in the noon-dawn local time sector. Triangles show crossings used in the A06 model. Some triangles do not lie on the Cassini trajectory line because these are crossings from the Voyager missions. Plus signs denote crossings used in the new model. The black circle at (0,0) represents Saturn’s position and the Sun is to the right hand side. Panel (b) shows a representation of the crossings in cylindrical coordinates to show the low-latitude coverage. Cassini’s trajectory for the period is the solid line. Again, the Sun is towards the right.
The temporal uncertainty in locating magnetopause crossings is not more than 10 minutes which corresponds to about $0.1 \text{ R}_s$. This is well within the root mean squared spread for the model values of magnetopause positions. The data consists of 191 crossings [McAndrews, 2007] which were spatially averaged to remove any bias due to boundary waves, rapid boundary motion and the spacecraft trajectory. Spatially averaging crossings within $1 \text{ R}_s$ of each other reduced the dataset to 68 crossings. Figure 43 shows the spatial distribution of the magnetopause crossings used in A06 and the new study. In figure 43a it can be seen that the crossings are well spread between local noon and the dawn flank/post-midnight sector at low latitudes. Figure 43b illustrates the distribution about the KSM X-Y plane and shows the predominance of the crossings near the equator. The lack of high latitude crossings may affect the outcome of the new study; this is discussed in further detail in section 4.4.
Figure 44: Histograms of pressure and plasma parameter distributions for the set of crossings used in this study; (a) magnetic pressure from the MAG instrument, (b) high energy particle pressure from the MIMI instrument, (c) low energy electron pressure from the CAPS-ELS instrument, (d) plasma beta, (e) and (f) total pressure contributions inside the magnetosphere (with and without individual components overlaid respectively).
Figure 44 shows the histograms of the distribution of the magnetospheric pressure inside the magnetopause for the crossings used in this study. The inclusion for the first time of internal pressures provides an excellent insight into the effects of the contributions of different partial pressures adjacent to the magnetopause inside the kronian magnetosphere. Figure 44a shows a histogram of the magnetic pressures inside the magnetosphere, taken from the MAG instrument. The magnetic pressure varies from $10^{-4}$ nPa to $<10^{-1}$ nPa (corresponding to field strengths between 0.5 and 15 nT) with a peak near $3\times10^{-3}$ nPa. This corresponds to a field strength of several nT which is common in Saturn’s outer magnetosphere (e.g. [Arridge, et al., 2008b]). Figure 44b illustrates the distribution of suprathermal particle pressures inside the magnetopause, taken from the MIMI instrument. Here pressures vary between $10^{-4}$ nPa and 1 nPa with a peak at approximately $3\times10^{-3}$ nPa similar to the magnetic pressure. Figure 44c shows low energy electron pressures inside the magnetosphere, from the ELS instrument. The pressures due to low energy particles are an order of magnitude less than the magnetic and suprathermal ion pressure, with a peak pressure of approximately $10^{-4}$ nPa, but the distribution has a width of around four orders of magnitude which is similar to the magnetic and suprathermal ion pressure. Figure 44d shows plasma beta inside the magnetopause which is found to range between $10^{-4}$ and $10^3$ and has a peak near 0.4, although the peak is quite broad extending between ~0.03 and 1.0. This highlights the importance of the magnetospheric plasma pressure for a large proportion of the magnetopause crossings in this study. Figure 44e and f, are thus dominated by the distribution of the suprathermal ion and magnetic pressure as the electron pressure is so small. These histograms also show
possible evidence of a bimodal distribution as discussed by Achilleos et al. [2008].

4.4 Results

Table 2 compares the values for the fitting coefficients and RMS values between observed and model r for A06 model and for the new model. The A06 and new models are also compared in figure 45. Firstly, the size coefficient $a_1$ is slightly larger than A06 but is in agreement with A06 within the estimated uncertainty. To first order, the introduction of additional sources of pressure inside the magnetosphere results in the estimated dynamic pressure being somewhat larger at each crossing. Hence, the model magnetopause will be slightly larger for the same dynamic pressure compared to A06.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>A06 model</th>
<th>New model</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_1$</td>
<td>9.7 ± 1.0</td>
<td>10.3 ± 1.7</td>
</tr>
<tr>
<td>$a_2$</td>
<td>0.24 ± 0.02</td>
<td>0.20 ± 0.3</td>
</tr>
<tr>
<td>$a_3$</td>
<td>0.77 ± 0.03</td>
<td>0.73 ± 0.07</td>
</tr>
<tr>
<td>$a_4$</td>
<td>-1.5 ± 0.3</td>
<td>0.4 ± 0.5</td>
</tr>
<tr>
<td>$\alpha$ value</td>
<td>4.3 ± 0.4</td>
<td>5.0 ± 0.8</td>
</tr>
<tr>
<td>RMS</td>
<td>1.238 (from A06)</td>
<td>3.603</td>
</tr>
<tr>
<td></td>
<td>3.82 (from new model)</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Values for the model coefficients and RMS comparing the A06 and new models. Using the new model crossings and A06 model coefficients the associated RMS was found to be 3.82, higher than the RMS for the new model.
The flaring parameter $a_3$ is slightly smaller in the new model compared to A06 resulting in a slightly more streamlined shape. This can be attributed to the direct inclusion of a dynamic pressure-dependent $P_0$ in the new model which increases the static pressure on the flanks and thus leads to a more streamlined obstacle. The pressure-dependent flaring parameter $a_4$ has changed the most between A06 and the new model; the large relative uncertainty on this parameter perhaps suggests that this parameter cannot be accurately resolved by the fitting technique and/or data set used.
Figure 45: The new model magnetopause shape. Panel (a) shows the new model magnetopause (dashed line) with plus signs denoting the new model, scaled crossings and the A06 model magnetopause (dotted line) with triangles denoting the A06 model, scaled crossings, both scaled to a standoff distance of 20 $R_S$. This gives a $D_P$ of 0.036 nPa and 0.043 nPa for the new model and A06 respectively. It can be seen that the new model is less flared. Panel (b) shows the new magnetopause shape scaled so that the standoff distance is at 21 $R_S$ and 27 $R_S$ giving a $D_P$ of 0.028 nPa and 0.008 nPa respectively. The direction perpendicular to the $X_{KSM}$ axis is $(Y_{KSM}^2 + Z_{KSM}^2)^{1/2}$. 
The power-law dependence of the dynamic pressure on the size of the magnetosphere is also consistent with A06 within the estimated uncertainties. The power-law $R_0 \sim D_p^{-1/\alpha}$ is described by $\alpha = 5.0 \pm 0.8$, compared to 6.1 for S85 and 4.3 $\pm$ 0.4 for A06. A power law exponent with $\alpha < 6$ indicates a magnetosphere that does not scale as a dipole with a fixed moment, but is more compressible, possibly giving evidence for the disc-like geometry that is thought to exist at Saturn [Arridge, et al., 2008b], enhanced plasma pressure within the disc, and response of the centrifugal component of the ring current to changes in system size [Bunce, et al., 2007]. Thus, whilst the inclusion of magnetospheric plasma pressure has modified the value of $\alpha$, the new value is still consistent with A06 and with the idea of a significantly compressible magnetosphere. This is in agreement with the results from MHD models presented by H05 but does not support the Pioneer/Voyager-era modelling in S85. Figure 45 illustrates the new model magnetopause shape compared to A06 (figure 45a) and for two different dynamic pressures (figure 45b). For figure 45a crossings were scaled for a common standoff distance and dynamic pressure, for both the new model and the A06 model, then plotted in order to compare the two models. The difference in the geometry of the new model with A06 is clear; the new model is less flared at the dawn and dusk flanks than the A06 model. For figure 45b the crossings have been scaled to standoff distances of 21 $R_S$ and 27 $R_S$ to represent high and low pressure solar wind conditions. The resulting common dynamic pressures are then plotted on the new model surface in order to visualise how the shape of the new model varies for different standoff distances. This method gives dynamic pressures of 0.028 nPa and 0.008 nPa respectively. Figure 45b shows the geometry of the new model.
Chapter 4: Saturn’s magnetopause

with magnetopause locations again scaled to represent high and low pressure solar wind conditions. The crossings are spread about the model, showing the validity of the assumptions used in the fitting. However, the crossings for this model are constrained to mainly dayside and lower latitudes so this will have a bias on the results. In particular it was not possible to identify a dawn-dusk or north-south asymmetry due to the axisymmetry of the model and the spacecraft coverage of the magnetosphere.

4.5 Discussion and future work

4.5.1 Variations between the models

Variations between the A06 and the new model are due to the expanded data set and the inclusion of variable solar wind thermal pressure and magnetospheric plasma pressure effects. The model derived in this study is close to that derived by A06 in their “high-beta correction”, although smaller, and so this also supports the idea that the A06 high-beta correction was over-correcting to some degree. Finally, the root mean squared value between the observed and model r is higher for the new model than for A06 but this might be expected due to the increased number of input parameters. The new model fitting algorithm was run using the best fit coefficient values for the A06 model as a starting point and the associated RMS was found to be 3.82 which shows that while the two models are similar, including actual magnetospheric plasma data in the new model gives different results. Any effects relating to periodic motion of the magnetopause (e.g. [Clarke, et al., 2006]) have not been included, but note that the peak-to-trough amplitude for such oscillations is around 2 Rs,
which is smaller than the RMS of the new model. Hence, such oscillations represent noise in the context of this work; these effects are not implicitly taken into account within the model, so future work may attempt to investigate whether the magnetopause is more or less compressible during such outward or inward periodic displacements.

4.5.2 A LARGER DATASET

Using further magnetopause crossings, any of which were available by the end of this thesis, was considered to be an initial aim for the model, but as time progressed other analyses, such as those discussed in further chapters, have become all encompassing, so it was not possible to return to this project in order to perform within the time frame of this thesis a full analysis using a larger database of crossings, hence making the model more current.

A comparison of the model dynamic pressures with actual measurements would be hugely beneficial in aiding its validity. The crossings used are primarily in the dawn sector at low latitudes which means that this model cannot account for any polar flattening effect but evidence for such an effect is being sought. A lack of high latitude crossings has prevented the investigation of this effect so future attempts to include these in the model would be important for the global understanding of the system. This would require altering the new model such that it was no longer axisymmetric thus allowed for high latitude crossing information.
4.5.3 **Solar wind speeds**

The new model used a range of estimated values for the solar wind speed at Saturn, based on previous measurements [Crary, et al., 2005] then the values were varied within the range to find the best fit parameters. Changing the solar wind speed did not appear to affect the model to a great degree. However, for a more accurate representation of Saturn’s magnetopause, actual values of the solar wind speed should be used, but this is not possible with a single spacecraft system. The closest available tool at present is the Michigan Solar Wind Model (mSWiM) ([http://mswim.engin.umich.edu/](http://mswim.engin.umich.edu/)).

This model can estimate solar wind conditions beyond the orbit of the Earth. The mSWiM uses in situ solar wind measurements made near Earth and other inner heliosphere locations and propagates these conditions to outer Solar System objects, such as Saturn, using a 1D MHD model. The inclusion of this model into the new magnetopause model would make it more accurate.

4.5.4 **Additional future work**

Other future work could include an investigation into the relationship between IMF clock angle and the magnetopause standoff distance [Achilleos, et al., 2008]. It has been suggested that the magnetosphere becomes more compressed for northward IMF, which might be expected if large-scale reconnection was occurring or if the magnetic field was eroded so that the magnetopause moves planetwards. In order to test this hypothesis it would be necessary to carry out a more detailed study of the magnetopause when more
crossings become available [J Cutler, private communication]. Other issues with the new model include the fact that as yet it has been assumed that the magnetopause is in equilibrium and is axisymmetric. Assuming a pressure balance also assumes that the magnetopause is static but in reality this is by no means necessarily the case. In order to ensure correct pressures have been accounted for it is imperative to have inbound and outbound crossings. If only fitting for inbound crossings, \( D_p \) is overestimated due to the fact that when a spacecraft enters the magnetosphere the magnetopause appears to be moving outwards which means the dynamic pressure decreases. The opposite can be said when the spacecraft travels from the magnetosphere into the magnetosheath; the dynamic pressure has increased since the magnetosheath pressure was measured, thus dynamic pressure estimates are generally too low because the magnetopause appears to be moving inwards.

This effect can be overcome by having equal numbers of inbound and outbound crossings, which should remove any bias due to the lack of equilibrium. With over 100 crossings in this study this should have been achieved, but future studies can only be more accurate due to the fact that there will be more crossings.

The axisymmetry of the new model is an oversimplification as the magnetosphere does vary diurnally, but the tilt between the magnetic field and the angle of rotation of the planet is very small so the diurnal affect is also very small. However there are also distortions in the tail region and due to the flapping of the current sheet, neither of which is included in the new model due
to the locations of the crossings. These types of distortions have been investigated in the MHD simulations of the H05 model.

4.6 Conclusion

A new model of Saturn’s magnetopause was created using multi-instrument Cassini data analysis. In the absence of an upstream monitor of the solar wind, dynamic pressures were calculated using an iterative process to fit a pressure balance model. New features of our model are a variable solar wind thermal pressure and use of direct measurements of the total magnetospheric plasma pressure. The results support the finding from A06 that the magnetopause size scales significantly differently to that expected of a dipole with a fixed magnetic moment. This indicates that internal magnetospheric plasma and centrifugal forces within the ring current are important in determining the pressure-dependent location of the magnetopause [Bunce, et al., 2007]. The inclusion of hot plasma pressure in the new model has not significantly changed this finding, although there is some evidence for a slight change in the overall size of the magnetopause for a given solar wind dynamic pressure.

As a result of including a dynamic pressure-dependent $P_0$, the new model has a less flared geometry. A sensitivity study was carried out to test the effect of the assumptions that were made regarding the static pressure and it was found that the model was insensitive to variations in solar wind speed and helium abundance. A further sensitivity study was carried out to evaluate the impact of any assumptions regarding the proton pressure inside the magnetosphere and it was found that the model was robust to variations in the assumptions. It has
been shown that the model has improved on previous models due to the inclusion of the suprathermal plasma and variable static pressures in the pressure balance equation providing more realistic results. Thus, at the present time, we suggest that it is the most accurate representation of Saturn’s magnetopause to date.
CHAPTER 5  A SURVEY OF INJECTION EVENTS AND AN INVESTIGATION INTO THEIR ROLE IN PLASMA TRANSPORT IN SATURN’S MAGNETOSPHERE

“Don’t make it sound like something you’d flip past on the Discovery channel.”

Spike, BTVS, episode 5.7.

This chapter discusses flux tube interchange and injection events in Saturn’s magnetosphere, as introduced in chapter 2 and chapter 3. Injection events occur when flux tubes containing tenuous, hot plasma from the outer magnetosphere interchange with cold, plasma rich flux tubes from the inner magnetosphere. Injection events are accompanied by drift dispersion events in which electrons and ions drift out of the flux tube and become separated over time. Injection events of interchanging flux tubes in Saturn’s magnetosphere have been observed between $L = 3$ and 13 and have previously been reported on by many authors, as will be discussed as this chapter progresses.

5.1 INTRODUCTION

The interchange instability in a plasma is akin to an MHD variant of the Rayleigh-Taylor instability for fluids, in which some regions of a high density fluid sitting on top of a low density fluid feel a gravitational pull due to fluctuations between the two fluids. The high density fluid ends up underneath the low density fluid as the two fluids exchange places. Both fluids feel a
This chapter discusses flux tube interchange and injection events in Saturn’s magnetosphere, as introduced in chapter 2 and chapter 3. Injection events occur when flux tubes containing tenuous, hot plasma from the outer magnetosphere interchange with cold, plasma rich flux tubes from the inner magnetosphere. Injection events are accompanied by drift dispersion events in which electrons and ions drift out of the flux tube and become separated over time. Injection events of interchanging flux tubes in Saturn’s magnetosphere have been observed between L = 3 and 13 and have previously been reported on by many authors, as will be discussed as this chapter progresses.

5.1 Introduction

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gravitational pull but parcels of high and low density fluid can swap places such that the rest of the system looks the same before and after the interchange. The gravitational potential energy of the system is smaller after the interchange therefore if the interchange can happen, it will. The initial state is an unstable equilibrium; the system evolves via the Rayleigh-Taylor instability towards a lower potential energy. This is because some of the released potential energy can be converted to kinetic energy.

In a plasma with a magnetic field both magnetic and plasma pressure are being exerted, thus interchange concerns both the plasma and the magnetic field in the form of a flux tube. A flux tube is defined as a region in space containing a plasma threaded with magnetic field lines running parallel to the flux tube’s axis and perpendicular to the local cross section of the flux tube. The cross sectional area and the local strength of the magnetic field in a flux tube may vary along its length, but the magnetic flux is always constant.

Interchange motion is important within a fast rotating planetary magnetosphere as it aids the transport of plasma and can help to explain the motion of flux tubes driven by centrifugal instability and plasma circulation.

For the Earth’s magnetosphere, it was originally thought that interchange motion was a spontaneous process but it was later proven that the circulation processes at Earth are not due to interchange instability but in fact driven primarily by the solar wind except in regions that are highly disturbed, where interchange may still occur [Gold, 1959; Southwood & Kivelson, 1987].

For the magnetospheres of fast rotating planets such as Saturn and Jupiter, centrifugal forces are important and the plasma sources and circulation
processes become more complex than for the Earth. Newly created plasma from internal plasma sources, such as the moons, has a lot of centrifugal potential energy that can be released if the plasma moves radially outward. If the incoming flux tubes gain less potential energy than the outgoing ones lose, interchange is favoured and expected to happen.

5.1.1 Pressure balance equations

The pressure balance equations derived in this section are from Southwood and Kivelson [1987] (herein referred to as SK87) unless otherwise stated.

Interchange instabilities depend on the system beginning in equilibrium and the instability being introduced as a plasma embedded in the magnetic field. The initial equilibrium is defined in equation 5.1.

\[ \nabla p - j \times B = nmg \]

5.1

If the system fluctuates away from equilibrium, equation 5.1 will change.

In interchange motion the flux tubes exchange and the field can vary in strength but SK87 use a simplifying assumption that the magnetic field lines do not bend appreciably during interchange motion, so the equations can consider small perturbations perpendicular to a steady field. The equations show that when the system is no longer stable, interchange can occur.

A perturbation velocity, \( u \), and a plasma displacement, \( u/\sigma \) (where \( \sigma \) is the growth rate of the instability), are introduced to the equilibrium equation. The
plasma displacement is considered to be time varying i.e. \( \exp(\sigma t) \). When the system is stable, there is no chance of interchange occurring. The system is stable when there are no displacements for which values of \( \sigma^2 \) are real and positive.

The changes in density and pressure are described in equation 5.2 and 5.3, where \( \gamma \) is the ratio of specific heats.

\[
\sigma n^1 = -n(\nabla \cdot \mathbf{u}) - \mathbf{u} \cdot \nabla n
\]  
\[5.2\]

\[
\sigma p^1 = -\gamma p(\nabla \cdot \mathbf{u}) - \mathbf{u} \cdot \nabla p
\]  
\[5.3\]

The change in the magnetic field is derived using the frozen in field equation, as expressed in equation 5.4.

\[
\sigma \mathbf{B}^1 = \nabla \times (\mathbf{u} \times \mathbf{B})
\]  
\[5.4\]

After some manipulation, as described by Southwood and Kivelson [1987], provided the field has not become bent, the equation for interchange motion is described in equation 5.5 where \( \mathbf{g}_{\text{perp}} \) is the gravitational field component perpendicular to the magnetic field, \( \mathbf{c} \) is the curvature vector and \( \mu_0 \) is the magnetic permeability.

\[
nm \sigma \mathbf{u} = -\nabla \left( p^1 + \frac{BB^1}{\mu_0} \right) + 2\mathbf{c} \frac{BB^1}{\mu_0} + n^1 mg_{\text{perp}}
\]  
\[5.5\]
After further manipulation, such as the scalar product of \( \mathbf{u} \) being taken and integrating over the volume in which the plasma is displaced, the equation becomes that as described in equation 5.6.

\[
\int nm \sigma^2 \mathbf{u}^2 dV = \int \left\{ P_{T} \left[ (\nabla \cdot \mathbf{u}) + \frac{\mathbf{u} \cdot \mathbf{u}}{P_{T}} \frac{\mu_{0}}{\gamma} \right] - \mathbf{u} \cdot (\nabla p - \nabla p_{cr}) \left[ 2 \frac{B^2}{\mu_{0}} (\mathbf{u} \cdot \mathbf{c}) + nm \mathbf{g} \cdot \mathbf{u} \right] \right\} dV
\]

\[5.6\]

In equation 5.6, \( P_{T} = (\gamma p + B^2/\mu_{0}) \), \( P_{T} \) is the total pressure \( (p + B^2/2\mu_{0}) \). The subscript CR denotes the critical pressure and density, as shown in equations 5.7 and 5.8.

\[
\nabla p_{cr} = \gamma p \left[ \frac{(\nabla B)}{B} + \mathbf{c} \right]
\]

\[5.7\]
If the system is stable no interchange will occur. If this is the case the right hand side of equation 5.6 must be positive. The first term on the right hand side is a square term so it is a stabilising term, always 0 or greater than 0.

In a fast rotating system, such as at Jupiter and Saturn, centrifugal force and Coriolis force must be added to the equation as these add to the gravitational force due to the planet. In this case, equation 5.5 is modified and angular velocity of the plasma, \( \Omega \), is introduced, to produce equation 5.9.

\[
\nabla n_{cr} = n \left[ \frac{(VB)}{B} + c \right]
\]

5.8

\[
n m \sigma u = -\nabla \left( p^1 + \frac{BB^1}{\mu_0} \right) + 2c \frac{BB^1}{\mu_0} + n^1 m g_{\text{perp}} - n^1 m [\Omega \times (\Omega \times r)]_{\text{perp}}
\]

5.9

It is also necessary to consider a centrifugally driven instability. It is important to realise that whilst hot plasma can exert a pressure, creating the interchange instability due to the \( \nabla p_{cr} \) term in equation 5.6, dense cold plasma with little pressure but higher centrifugal forces, can also play a part in making the flux tube unstable, due to the \( \nabla n_{cr} \) in equation 5.6. The question of whether a particular system is interchange unstable thus depends on the relative contributions of pressure and density, sometimes with competing effects. For a situation in which more cold plasma is present, the plasma pressure does not exert as much force as the centrifugal force. The equilibrium force is maintained by an effective gravity in a direction perpendicular to the field.
The effective gravity, $g_E$, is explained by equation 5.10.

$$g_E = g - \Omega \times (\Omega \times r)$$

5.10

In an idealised system the magnetic field lines can be assumed to be straight hence only one of the terms in equation 5.10 dominates. In a magnetosphere, both centrifugal force at the equatorial region of the flux tube and gravitational force near the ends of the flux tube can be important, so both terms are necessary.

Examples of situations in which there is a rapidly rotating but low-pressure plasma are the Io plasma torus at Jupiter and the torus of Enceladus at Saturn, where the centrifugal force is more important than the pressure.

For this low pressure, centrifugally driven situation, the original equation is extrapolated into equation 5.11, in which the pressure terms are not included because of the fact that the centrifugal terms are more important.

$$\int n\sigma^2 u^2 dV =$$

$$= - \int \left[ \frac{B^2}{\mu_0} \left\{ (\nabla \cdot u) + u \left( \frac{(\nabla B)}{B} + c \right) \right\} \right]^2$$

$$+ (mg \cdot u) \left\{ (u \cdot \nabla n) - nu \left( \frac{(\nabla B)}{B} + c \right) \right\} dV$$

5.11
These equations demonstrate the conditions for an interchange instability to occur, taking into account variations in plasma pressure, centrifugal force and a low pressure situation, giving rise to interchange motions [Southwood & Kivelson, 1987]. However it is assumed that the plasma has an isotropic pressure, which is not realistic. For equations relating to anisotropic cases please see Fazakerley and Southwood [1993].

5.1.2 Formation processes of low density, high pressure flux tubes

5.1.2.1 Earth

Magnetic substorms and the Dungey cycle drive much of the plasma transport at Earth. Substorms at Earth occur during or after times of southward orientation of the interplanetary magnetic field when reconnection at the dayside drives the merging of terrestrial and heliospheric magnetic field lines. The newly opened magnetic flux is transported towards the magnetotail and energy is released. There are three phases of a substorm: the growth phase, the expansion phase and the recovery phase, as shown in figure 46.

During the growth phase dayside reconnection occurs and the eroded flux from the magnetopause is transported to the magnetotail, adding open magnetic flux to the tail. Some of the flux is reconnected and convected back towards the dayside magnetosphere. The flux that is added to the tail causes the tail lobe magnetic field to increase, and because the tail lobe magnetic flux and the neutral sheet current are related by the Biot-Savart law, the neutral sheet current increases as well. The neutral sheet current growth stretches the magnetic field lines, which cause the plasma sheet to also stretch, into a more
tail like configuration. Eventually there is too much magnetic flux built up in the tail and the system becomes unstable, leading to the expansion phase.

Throughout the expansion phase the magnetic field becomes more dipolar due to reconnection occurring. One model of substorm formation is the Near Earth Neutral Line (NENL) model [Baker et al., 1996]. The NENL is formed in the tail (there is a Distant Neutral Line (DNL) further out in the tail) and this X-line allows the reconnection of the excess magnetic flux in the tail that built up during the growth phase. After reconnection, the stretched field lines are able to return to a more dipolar shape. The region between the two neutral lines forms a plasmoid. The magnetic field lines in a plasmoid form closed loops.

For the duration of the recovery phase the system returns to a pre-storm configuration. Reconnection ceases and stretched field lines eventually return to a more dipolar shape, until the onset of the next substorm when the dipolar field lines start to stretch again. The NENL retreats tailward and pushes the plasmoid with it, until eventually the plasmoid is ejected from the magnetotail. The plasma is released into the solar wind and the NENL becomes the DNL.

It is possible that substorms are linked to interchange instability as newly reconnected closed flux tubes could be interchange unstable. The reconnection produces fast flows in the plasma sheet that propagate towards the Earth, known as bursty bulk flows (BBFs). The BBFs carry magnetic flux with them as they travel earthwards. It has been suggested that BBFs are depleted flux tubes, known colloquially as plasma bubbles. Bubbles were suggested by Pontius and Wolf [1990] as a solution to the pressure imbalance caused by the adiabatic transport of magnetic flux and plasma earthward by the BBFs. Bubbles are of
interest in this thesis as they could be a useful diagnostic of plasma sheet transport and the injection of the closed flux tubes in the magnetotail [Birn et al., 2004; Birn et al., 2011; Pontius Jr & Wolf, 1990; Sergeev et al., 2012; Walsh & Forsyth, 2011].

![Injection events diagram](image)

**Figure 46: Substorm growth, expansion and recovery.**

From [Baumjohann & Treumann, 1997].

### 5.1.2.2 Jupiter and its applicability to Saturn

Injection events at Jupiter are created through different processes to those at Earth. They occur due to the fact that Jupiter is a fast rotator, dominated by the
Io plasma source which creates the Io plasma torus. Injection events are observed between 9 and 27 jovian radii from the planet [Mauk et al., 1997; Mauk et al., 1999]. Like Jupiter, Saturn is a fast rotator and has a strong internal plasma source within its inner magnetosphere.

The interchange instability at Jupiter has been investigated by many authors [Kivelson & Southwood, 2005; Kivelson et al., 1997; Thorne et al., 1997]. As discussed previously, in the case of the Earth, interchange instabilities tend to occur on the night side due to the Dungey cycle and magnetic substorms. At Jupiter and Saturn they are also observed on the dayside within the plasma disc that is apparent at each planet, and due to centrifugal forces.

Jupiter’s plasma disc dominates the dawn-morning magnetosphere beyond approximately 20 $R_J$ ($1\,R_J = 71,492$ km) and it contains a thin current disc of thickness about 2 to 4 $R_J$. It has been observed that in the noon-afternoon sector the plasma disc is thicker than in the pre noon morning sector [Kivelson & Southwood, 2005]. The rotating plasma disc is well defined by a model in which Io ejects material into the inner magnetosphere. The ejected neutrals are ionised and picked up at Io’s corotation energy, creating cold plasma. This plasma is constrained near the magnetic equator by the centrifugal force acting upon it and over time it will move outwards, leading to the material sub-corotating. This motion has an effect on the interchange instability process; the inner magnetospheric sources render the system naturally unstable which can cause spontaneous injection events in order to reach stability once more [Southwood & Kivelson, 1989]. It is thought that this type of interchange motion happens impulsively because Io ejects material at varying rates, filling
flux tubes until the instability criterion described earlier is met and interchange starts.

Kivelson and Southwood [2005] describe the system as including motions that are said to 'balloon', as described in figure 47.
This is similar to the idea of a substorm but arises from the changing magnetic configuration due to centrifugal forces in a rotating system. When the outer
edge of the disc comes around from the day to the night it is able to expand outwards because there is no magnetopause confining it, thus the centrifugal forces on the cold plasma at the equator are able to grow. The inward force that acts against the centrifugal force to keep the plasma going round the planet is the $j \times B$ force due to an azimuthal current in the magnetodisc, which is connected via a field aligned current to an azimuthal current in the ionosphere. If this current system can't provide enough current, for example if the ionosphere is too resistive, there is not enough radially inwards force so material can break away and fly off.

This breaking off can also occur in the disc at other local times if a flux tube becomes highly mass loaded, for example by Io, because the more mass loaded a flux tube becomes, the more force is required to balance the centrifugal force.

At Saturn, the disc always extends to the magnetopause but at Jupiter, when the solar wind pressure is low, the magnetopause moves further out than the outer edge of the disc. This means that the disc is unable to remain in corotation out to the magnetopause so the break off can occur on the dayside as well. It is thought that some of the original flux tube content will break off as a bubble, leaving a depleted flux tube behind. It is expected that the depleted flux tube would then travel back towards the planet due to interchange motion. This ballooning process is important because it could possibly explain how flux tubes can lose material at the edge of the plasma disc and hence suddenly become buoyant and tend to move. This process can explain why, at Jupiter and Saturn, injection events can also occur on the dayside.
The position of the planetary magnetopause in relation to the solar wind can also affect the rate of injection events. At dawn, the jovian plasma sheet is thin and extended as it experiences the least amount of pressure from the magnetopause. On the dayside, the plasma sheet becomes thicker and extends over a shorter radial distance because it is constrained or braced by the position of the nearby jovian magnetopause. This thickening can cause an instability which leads to the ballooning and break off described previously. In the dusk sector, the plasma sheet becomes irregular and is still quite thick, and this leads to it being almost indistinguishable from the outer magnetosphere. This is partly due to the heating that takes place between the noon and dusk sectors. The thick plasma sheet is confined by the magnetopause and plasma loss from it is inhibited by the pressure exerted on it from the magnetopause. On the nightside, outflow occurs because pressure exerted by the outer region is much lower than on the dayside so the sheet becomes elongated and thinner until, in the post midnight sector, plasmoids are released and the remaining flux tubes become depleted [Kivelson & Southwood, 2005]. This indicates that only nightside or dusk flank injection events should be observed.

This description of the jovian system by Kivelson and Southwood [2005] demonstrates that the Vasyliunas cycle idea models what is seen approximately but additions are needed in order to account for the dayside injection events. The dayside injection events occur because Jupiter has internal sources of plasma and is a fast rotator, a schematic of which is shown in figure 47. These conditions are not applicable to Earth but are, for the most part, applicable to Saturn.
Ubiquitous injection events in the kronian magnetosphere are thus more likely to be caused by centrifugal interchange instabilities, due to density and pressure gradients and rotation speeds, than the solar wind driven convection i.e. substorm-like events which occur at Earth.

Observations suggesting injection events have been made by the CAPS instrument since Saturn orbit insertion (SOI). Burch et al. [2005] and Hill et al. [2005] argued that these interchange instabilities cause magnetic flux tubes of cold, dense plasma to move away from Saturn, being replaced by hot, tenuously populated flux tubes moving towards Saturn, themselves generated through previous episodes of mass loss from the outer plasma sheet. At present, individual flux tubes of hot plasma have been observed moving towards Saturn, but not moving away from Saturn. The injections analysed in these papers are observed out to $L = 12$.

The reason the flux tubes become unstable and move outward is thought to be due to the inner flux tubes being populated by plasma from sources such as Enceladus. Once populated, they tend to move radially outwards due to centrifugal forces. Interchange requires that the outward flow is balanced by a flux tube from the outer magnetosphere moving towards the planet. It is this motion that is observed as injection events.
5.1.3 **An example injection event**

Figure 48 shows an example injection event, of the ilk of those surveyed in previous papers e.g. [Chen & Hill, 2008; Chen et al., 2010]. Figure 48a is an electron log energy-time spectrogram from the 24th October 2004 spanning an 80 minute period, during which there are copious short duration injection events. Figure 48b is an ion log energy-time spectrogram showing the same time period. Comparing the plots, it can be seen that the ion injection events disperse in the opposite direction to the electron events. The injections have the following drift dispersion profile as seen from the relatively slow moving Cassini spacecraft; high energy ions first, low energy ions, low energy electrons then high energy electrons last, consistent with the magnetic drift dispersion theory. When the spectrograms are plotted against a linear energy range, as shown in figure 49, half a ‘V’ shape is formed with the ion injection event first and then the other half of the ‘V’ for the electron injection events, completing the ‘V’ shape. The apex of the V is the centre time of the injection. In order to calculate the age of an injection, a spectrogram is plotted linearly and the gradient of an energy-time slope is utilised. The gradient varies for different events due to a different time elapsed since injection, described in more detail in section 5.1.4.
Figure 48: Injection events over an 80 minute time span on the 28th October 2004.

a) Anodes summed electron energy-time spectrogram. b) Anodes summed ion energy-time spectrogram. Both are plotted with a log energy scale in differential energy flux.
5.1.4 Calculating the Age of an Injection Event

Hill et al. [2005] formulated the calculation of the age of the dispersion features, i.e. the length of time since the injection event occurred. Injection event ages in this survey were calculated using this technique. The derivation of this equation follows, starting with the equation for magnetic gradient drift, equation 1.18 in chapter 1, repeated here as equation 5.12:

Figure 49: Injection events over an 80 minute time span on the 28th October 2004.

a) Anodes summed electron energy-time spectrogram. b) Anodes summed ion energy-time spectrogram. Both are plotted with a linear energy scale.
where $E_{\text{perp}}$ is the perpendicular energy.

Assuming that the field is dipolar, the gradient-curvature drift speed in the equatorial plane can be extrapolated in the following way, to give the magnetic field strength at the magnetic equator:

\[
B = \frac{B_0 R_S}{R_S^3 L^3} = \frac{B_0 R_S}{r^3}
\]

where $L$ is the $L$-parameter and $B_0$ is Saturn’s surface dipole field strength at the equator which is $21 \, \mu$T. The cross product can be expanded as shown in equation 5.14.

\[
B \times \nabla B = B \times \frac{dB}{dr} = B \times \frac{-3B_0 R_S}{r^4} = B \times \frac{-3B_0 R_S}{r^4} = B \times \frac{-3B_0}{r} = \frac{-3B^2}{r}
\]

This gives a final equation for the drift velocity, as shown in equation 5.15.

\[
V_g = \frac{E_{\text{perp}}}{qB^3} \left( \frac{-3B^2}{r} \right) = \frac{-3E_{\text{perp}}}{qBr} = \frac{-3\mu}{qr}
\]
where $\mu$ is the magnetic moment of the particle, $q$ is the charge and $r$ is the radial distance to Saturn. Because at the equator $r=R_S L$ and $B=B_0/L^3$, equation 5.15 can also be written as equation 5.16.

$$V_g = \frac{-3E_{\text{perp}}L^2}{qR_SB_0}$$

5.16

Another approximation was made: it was assumed that the undispersed particle population was injected instantaneously at a time $t_0$ at the distance of the observation and then began to disperse longitudinally at that distance with no further radial motion.

For a given magnetic moment, $v_g$ varies as $1/r$. The angular drift rate is $d\phi/dt = v_g/r$ hence the angular drift rate varies as $1/r^2$. The radial injection speed, due to the $E\times B$ drift, is a strongly increasing function of $L$ shell, so it is reasonable to assume that a large fraction of the observed drift dispersion occurs at an $L$ value close to that of the observation.

After a time $T_{inj}$ since the injection event a particular particle will have drifted through a longitude angle $\Delta\phi$ given by equation 5.17.

$$r\Delta\phi = v_g T_{inj}$$

5.17

Equation 5.17 can be substituted into equation 5.16, giving the following:
The longitude difference, $\Delta \phi$, is also related to the observation time of the injection ($T_{inj} = t - t_0$) relative to the observation time, $t_0$, of the apex of the V shaped dispersion event. This gives equation 5.19.

$$\Delta \phi = \Omega (t - t_0)$$

5.19

$\Omega$ is the angular speed at which the longitudinal structure sweeps past the spacecraft, as the magnetic drift is measured in the corotating frame moving with the angular speed $\Omega$. For the equation in Hill et al [2005] the spacecraft is assumed to be fixed in local time during the dispersion signature. Again the equations can be substituted, this time placing equation 5.19 into equation 5.18, then differentiating with respect to time to give the slope of the energy-time curve (a straight line on a linear energy-time plot), giving equation 5.20.

$$\frac{dE}{dt} = \frac{q B_0 R_S^2 \Omega}{-3L T_{inj}}$$

5.20

Equation 5.20 can be rearranged so that the time since injection becomes the focus of the equation. This is shown in equation 5.21, with constants replaced by actual values. The ratio of angular speed, where $\Omega$ is the value at the injection site and $\Omega_S$ is the value for Saturn ($2\pi/10.8\text{hr}$), takes the possible deviation from corotation into account, according to values expressed by Wilson et al. [2008]. This is a new modification to the Hill et al. [2005] equation
that takes into account new knowledge of the plasma flow learned since the equation was first formulated [T. Hill, private communication]. $T_{\text{inj}}$ is in the units of hours and $dE/dt$ is in keV per minute. Very fresh injections have an immeasurably small slope and very old injections have immeasurably large slope or they fade away before the slope gets too shallow.

$$T_{\text{inj}} = \frac{-6.9 \left( \frac{10}{L} \right) \left( \frac{\Omega}{\Omega_z} \right) q}{\frac{dE}{dt}}$$

5.21
An illustrative example is shown in figure 50, where the $dE/dt$ slope is highlighted in black. The slope fitting is done manually and is therefore subjective, thus carries an amount of error estimation with it. During an assessment of the size of errors on the placement of the slope, maximum and minimum slopes were fitted along with the best guess slope. It was observed that within these boundaries on the slope the effect in the estimation of $T_{\text{inj}}$ was minimal as the ages varied by a maximum of $\pm 10$ minutes.
5.1.5 Pitch angle distributions

It has been proposed that the direction of motion of the flux tubes, and hence the source locations, can be inferred from the analysis of pitch angle distributions, sometimes referred to as PADs [Burch, et al., 2005; Rymer et al., 2008]. These distributions can generally be qualitatively classified into four shapes, each indicating a different process in which plasma is radially and adiabatically transported within a dipole field. Assuming that the first and second adiabatic invariants are conserved, simulations of the change of pitch angle distributions with adiabatic radial plasma transport were carried out [Rymer, et al., 2008]. The assumption that inward radial transport of charged particles conserves the first and second adiabatic invariants, resulting in pitch angle-dependent heating, has been used previously. Loss-free, scatter-free radial plasma transport conserves the first adiabatic invariant and the second adiabatic invariant is expected to be conserved in the absence of bounce-resonant field variations [Arridge, et al., 2012]. The isotropic distribution has constant flux over all pitch angles. The pancake distribution has peak fluxes at 90°, i.e. locally trapped electrons. The field aligned distribution has peak fluxes at 0° and 180° pitch angle and the butterfly distribution has troughs at 0°, 90° and 180° pitch angles. These are shown as cartoons in figure 51 with real data shown later in the chapter.
Pancake distributions were shown to occur when there was inward transport of an isotropic distribution of energetic particles from larger L shells to smaller ones and field aligned distributions occur with outward transport of an isotropic distribution. The butterfly distribution was more complex; it was shown to indicate the outward transport of a pancake distribution but it was only possible to recreate the butterfly distribution if non-adiabatic processes were also included in the simulations [Rymer, et al., 2008]. These pitch angle distribution processes are shown in figure 52.

Figure 51: a cartoon showing pitch angle distribution shapes. The green line is a field aligned distribution, the red line is a pancake distribution, the purple line is an isotropic distribution and the blue line is a butterfly distribution.
The pitch angle analysis gives rise to models of the dynamics of these injection events. The cold electrons inside \( L = 13 \) are thought to arise from the ionization of the neutral cloud. These electrons are heated via Coulomb collisions and flow outward due to centrifugal instabilities, becoming the source population for inward travelling injection events, also due to centrifugal instabilities. The inward moving hot electrons are assumed to conserve the first and second

**Figure 52:** How pitch angle distributions change as a flux tube moves inwards from a greater \( L \) value to a lower \( L \) value. The transport for the top two processes is assumed to be adiabatic, thus can be considered to be fully reversible, so the figure is applicable in the opposite sense, i.e. outward.

This is not applicable for the third process in which the outward transport of a pancake distribution gives rise to a butterfly distribution, because the process is non-adiabatic and therefore not reversible, i.e. the adiabatic inward transport of a pancake distribution does not give rise to a butterfly distribution.
adiabatic invariants and tend to show a pancake pitch angle distribution with a peak at 90° if assumed to be isotropic initially. Inside the injection events, at lower energies, it can be shown that a field aligned pitch angle distribution is present, possibly indicating flux tube-ionosphere coupling [Rymer, et al., 2008].

Butterfly pitch angle distributions for low energy electrons have also been observed neighbouring hot plasma injections [Burch et al., 2007]. These have been interpreted to signify radial plasma outflow from sources such as the exospheres of moons, due to specific pitch angles corresponding to electron energies and radial distances to Saturn. However, Rymer et al. [2008] were not in agreement with this suggestion due to the fact that there were no clear generation mechanisms to create these low energy electrons from such a source and they preferred the model of recirculation of electrons from the outer magnetosphere creating such an internal source.

Another mechanism that may produce butterfly pitch angle distributions is the absorption by dust particles residing in Saturn’s E ring [Burch, et al., 2007; Jones, et al., 2006]. The E ring extends from L = 3 out past L = 9 and is densest around the equator. Particles which have low latitude mirror points hence pitch angles of approximately 90°, would reside in the equatorial plane and thus be the ones most likely to be absorbed.
5.2 **Injection events at Jupiter**

It is useful to study injection events observed at Jupiter due to the fact that the planet has many similarities to Saturn. By learning about creation mechanisms and circulation patterns at Jupiter it is possible to draw more educated conclusions from kronian injection data, henceforth injection event observations at Jupiter are discussed in this section.

Rapid inward transport has been seen at Jupiter, such as the event on the 7th December 1995 studied by Thorne et al. [1997] and Kivelson et al. [1997] using data from the Galileo spacecraft. The injections are thought to occur due to rapid mass loading from the Io plasma torus, leading to the interchange instability as described previously. The injection event lasted ten seconds during which the magnetic field magnitude increased by 22 nT, with coincident enhancements in the count rates of energetic ions and electrons. A pitch angle distribution analysis showed that before and after the event the pitch angle is mostly isotropic but slightly pancake, and during the event the trapped electrons are more prominent and strong pancake PADs are observed [Thorne, et al., 1997]. This is consistent with the Rymer et al. [2008] idea for an initially isotropic distribution.

The conclusions from the data for this event are that a low mass flux tube, travelling rapidly inwards towards Jupiter from the outer torus was observed. However it is mentioned that the pitch angle distributions indicate drifting into as opposed to out of a flux tube as expected by the Rymer et al. [2008] model, but this is not expanded upon. Previous studies of these types of interchange
have denoted transport occurring in individual flux tubes which have the same dimensions in azimuthal and radial directions [Southwood & Kivelson, 1989], or in finger like structures which are elongated in the radial direction [Yang et al., 1994]. Using simple mechanics it was estimated that the azimuthal extent of this flux tube was 600 km if the finger like structure was assumed, and a minimum inferred velocity of 83 km/s. If an individual flux tube structure was assumed, the size was approximately 700 km and the minimum inferred velocity was 70 km/s. It is interesting that there is a lack of signatures inside of Io’s orbit as this would fit with the idea that the plasma production at Io acts to fill flux tubes causing them to become dense and move outward, interchanging with inward moving flux tubes that have a lower density. Alternatively it could be due to a lack of spacecraft coverage inside of Io’s orbit, as Galileo did not pass inside of Io’s orbit on many occasions.

5.3 Injection events at Saturn; current results

Injection events of interchanging flux tubes in Saturn’s magnetosphere have been observed between L = 3 and 13, in an area where there are many plasma sources such as the Kronian moons; these have previously been reported on by several authors e.g. [Burch, et al., 2005; Hill, et al., 2005]. Studies of injection events have examined ion and electron energy-time dispersion profiles and inferred source locations e.g. [Rymer, et al., 2008] but as yet a direct determination of the radial direction of the plasma flow towards or away from Saturn has not been reported.
Injection events have been observed by the magnetometer (MAG) as local variations (increases and decreases) in magnetic field strength and by the Cassini Plasma Spectrometer (CAPS) and the Magnetospheric Imaging Instrument (MIMI) as sharp changes in plasma density and temperature, interpreted as flux tubes accompanied by longitudinal magnetic gradient and curvature drifts because the electrons and ions have magnetic and curvature drift in opposite directions, causing the dispersion features of the injection events. This arrangement leads to the energy-time dispersion patterns viewed in the CAPS and MIMI data, but these patterns do not indicate the type of formation process i.e. do not indicate whether the cause is centrifugal interchange or solar-wind driven processes.

The occurrence of injection events has been observed to have a dependence on energy, radial distance, local time, Saturn Longitude System (SLS) longitude and pitch angle. A dependence has been observed showing larger electron fluxes on the night side of the magnetosphere according to injection events measured using the LEMMS instrument, with an energy range of 20 keV up to 1.7 MeV [Paranicas, et al., 2010]. A peak in energy flux for low energy electrons (12 – 100 eV) at 8 R₅ and particularly on the night side for trapped low energy electrons has been attributed to injection events [DeJong et al., 2010].

A preference for injections to be observed in the pre-noon/morning sector has been demonstrated by Chen and Hill [2008]. Injection events have been observed between 9 and 15 LT and source locations of these injection events observed in MIMI data have been inferred to be in the dawn and night sectors [Müller, 2011]. DeJong et al. [2011] showed that low energy electrons (12 –
100 eV) associated with injections are also dependent on local time; indicating a day-night asymmetry in the injections themselves with enhanced energy fluxes on the nightside over the dayside. Mitchell et al. [2009] used the detection of energetic neutral atoms (ENAs) by the Ion and Neutral Camera (INCA) onboard Cassini to infer the presence of injection events on the nightside of Saturn's magnetosphere, between midnight and dawn local time. An increase in energetic neutral particles can indicate that an injection event has taken place, particularly in an area of greater neutral gas density because there is scope for charge exchange and ionisation, hence the production of ENAs. Whilst these ENA events are found at large radial distances, they have been shown to be associated with injection events [Müller, 2011].

It has been shown that electrons with pitch angles of around 90° are mostly observed to have longitudes in the Saturn Longitude System 3 (SLS3) coordinates between 45° and 240° at L = 7.5 and SLS3 coordinates between 310° and 360° at L = 5.5, with no apparent SLS3 dependence for electrons that are field aligned [DeJong, et al., 2010]. The majority of the trapped electrons probably come from Enceladus since plasma is created in the equatorial plane thus will have a trapped pitch angle dependence. The field aligned electrons could be due to interchange injections rather than from the source at Enceladus, because injection events have previously been shown to have no SLS3 dependence [Chen & Hill, 2008].

Results from Chen and Hill [2008] and Chen et al. [2010] show injection events with ages less than 28 hours, the majority of which are less than 6 hours old. Most are less than 1 Rs in longitudinal width (which is calculated by
multiplying the width in time with the partial corotation velocity), but the width limit is partly due to the specifications of their survey. Whilst the injection events are spread over all local times, the majority of injections are between 4 and 12 LT, in the pre noon quadrant. As only 5-10% of available longitudinal space is taken up by injections perhaps this demonstrates that Saturn’s rotation driven convection system is dominated by broader regions of slowly outflowing material and narrow sections of rapidly inflowing material.

5.3.1 Plasma flow models

Aspects of the nature of plasma injections within Saturn’s magnetosphere are still unresolved. The overall concepts of hot injections migrating inwards and a general radial outflow of cooler plasma are generally agreed upon but in terms of the nature of plasma injection and controversies about the outflowing plasma there is still much to be determined.
Many models lean towards the idea that kronian injection events have ‘finger’ like shapes as they arrive from the outer magnetosphere and disperse in order of energy. The inward moving dispersion features occur alongside the cooler outward flowing locally produced plasma [Hill, et al., 2005]. The ‘finger’ of plasma is able to permeate the inner magnetosphere, carving a density cavity and bringing hot plasma into the inner region [Burch, et al., 2005]. This is described in figure 53 and expanded upon by Rymer et al. [2008] who describe a system in which warm (above 100 eV) plasma disperses out of an inward flowing flux tube onto flux tubes carrying mostly cold plasma that are moving outward by interchange motion.

Figure 53: Cartoon showing an injection event of hot tenuous plasma towards Saturn, interchanging with dense, cold plasma flowing radially outward. The finger shaped injection adiabatically gradient and curvature drifts, causing the dispersion signatures shown in figure 48. From Hill et al. [2005].
This outward motion is associated with the butterfly pitch angle distribution, but the butterfly distribution can only be modelled using adiabatic transport and convection, together with losses due to interactions with neutrals in the surrounding environment.

Burch et al. [2005] formulated a model for the plasma transport process, a cartoon of which is shown in figure 54, showing figure 53 in the context of the whole system.

![Cartoon showing an interchanging flux tube drawn as a finger of plasma, in a Saturn fixed frame of reference looking at Saturn from the north with the Sun at the top. The inward moving flux tube is entering the inner magnetosphere from the night side. A finger of plasma is thought to be more than one flux tube or a flux tube with an associated wake. From Burch et al. [2005].](image)

However, it is also possible that the injections occur as discrete bubbles of plasma, similar to plasma transport at Earth. Angelopoulos et al. [1992] and
Baumjohann et al. [1990] showed that at the Earth the sunward convection of magnetic flux in the plasma sheet could actually be due to many inward bursty high speed flows integrated with irregular intervals of near stagnant plasma. It has been argued that bursty bulk flows are a significant type of interchanging flux tubes which can produce the energy, momentum and magnetic flux transport necessary for an expected steady state convection pattern. At Earth, the mixture of intervals of BBFs and intervals of near stagnant plasma could lead to the steady sunward convection of the plasma sheet [Angelopoulos, et al., 1992; Baumjohann, et al., 1990]. It is possible that bursty bulk flows, or a combination of fingers and bubbles, is occurring at Saturn. These ideas are shown as a cartoon in figure 55.

Figure 55: Cartoon showing a) injections as complete fingers of plasma and b) injections as a mix of fingers and bubbles of plasma. The cartoon is in a Saturn fixed frame of reference looking at Saturn from the north.

Figure courtesy of G. H. Jones.
A global representation of plasma injection patterns at Saturn was created by Müller [2011] and is shown in figure 56. In figure 56 the injection events observed in the survey by Müller [2011] using the MIMI instrument are separated in terms of intensity (where intensity is defined as $I=\text{counts}/(\Delta E \cdot G)$ and $\Delta E$ is the energy passband and $G$ is the geometric factor) over the whole energy range of the MIMI-LEMMS instrument, 20 keV to approximately 130 MeV. The yellow semicircle denotes injections with low intensity, less than

Figure 56: Cartoon showing plasma injection sites and observations in the kronian magnetosphere. Green arrows show inward and outward flow of plasma. The orange arc shows an area of energetic neutral atom emission as observed by Mitchell et al. [2009]. The red semicircle shows injections with high intensity. The yellow semicircle shows injections with low intensity. Saturn is viewed from the North Pole, magnetic local times in hours are indicated by numbers and the Sun is on the right hand side. From Müller [2011].
Chapter 5: Injection events

2x10⁴ cm⁻²sr⁻¹s⁻¹, and these are observed from 12:00, through 18:00 to 24:00 LT. The red semicircle denotes injections with a high intensity, greater than 2x10⁴ cm⁻²sr⁻¹s⁻¹, and these are observed from 00:00, through 06:00 to 12:00 LT. It is possible that the high intensity injection events could also be associated with the reconnection processes associated with the Vasyliunas- and Dungey-cycle X-line [Müller, 2011]. Green arrows indicate plasma assumed to be moving towards (inward) and away from (outward) Saturn. The thick orange semicircle in the midnight-dawn sector denotes where energetic neutral atoms are observed [Mitchell, et al., 2009]. This is important in terms of injection events because this is the region associated with reconnection processes in the magnetosphere. This reconnection is thought to be a driver for injection events observed by the INCA instrument between dawn and midnight in local time [Mitchell, et al., 2009]. At Saturn it is believed that there is more than one process generating injection events; those due to reconnection and those due to centrifugal interchange instability [Müller, 2011]. The latter, in theory, should be able to occur at any local time.

5.3.2 Magnetic field signatures

When viewed in conjunction with other datasets, Cassini magnetometer data provide evidence for signatures of interchanging flux tubes as localised increases (as at Jupiter) and decreases (not yet seen at Jupiter) in magnetic field magnitude. Generally it is thought that a decrease in magnetic field strength indicates entry into an inward moving flux tube. This is because it implies a reduction of magnetic pressure which must correspond to an increased plasma pressure to conserve total pressure, and the hotter higher
pressure plasma is found at larger distances from Saturn. The energy density of the hotter outer magnetosphere plasma is greater than that of the cold plasma in the inner magnetosphere because the magnetic field strength decreases with distance from Saturn. Flux tubes with cold plasma could have higher or lower energy density depending on their specific densities and temperatures. At Saturn it is the outer hot tubes that have more plasma pressure than the inner cold tubes, therefore an increase in magnetic field strength is believed to indicate a decrease in plasma pressure and an outward moving flux tube [C. Russell, private communication]. On one occasion [André et al., 2007] both types of magnetic field signature have been taken to indicate an inward moving flux tube devoid of cold plasma. André et al. [2007] found that signatures with increases in magnetic field strength are concentrated close to the equatorial plane and those with decreases away from the equatorial plane. Thus, it was deduced that the magnetic field fluctuations are latitudinally affected due to temperature gradients at higher latitudes affecting the pressure balance. At higher latitudes the plasma is hotter and the magnetic field strength is lower in order to retain the pressure balance.

Whilst the magnetic signatures are consistent with the expected interchange of cold dense and hot tenuous plasma, the details of the outward flow remain elusive. It is currently believed that outward transport does not occur as isolated events, but rather as a general plasma outflow across a broad range of local times [Rymer, et al., 2008]. This could indicate that the circulation of plasma in the kronian magnetosphere replicates the plasma circulation in the jovian magnetosphere.
However, magnetic field strength enhancements have been observed coincident with a small number of injection events and these have been interpreted as showing outward moving flux tubes [Russell et al., 2006]. If these magnetic field enhancements are indicative of mass-loaded plasma being transported downtail as isolated events rather than a general outflow, as suggested by Russell et al. [2006], it could mean that the circulation of plasma in the kronian magnetosphere does not follow the plasma circulation in the jovian magnetosphere, previously proposed by Vasyliunas [1983] and Russell [2001].

5.4 Motivation for the survey

Injection event surveys have been carried out, for example, by Chen and Hill [2008] who analysed CAPS data from SOI on the 30th of June 2004 to the end of August 2006, between L = 5 and 10. However, very young events and very large scale events were not included and only CAPS data were used. An update to the survey in 2010 (which also only used CAPS data) [Chen, et al., 2010] looked at the same time period (2004-2006) but extended the survey to include younger events. Surveys using the MIMI instrument have also been carried out e.g. Müller [2011], covering a time period between mid 2004 and late 2007, for energies from 10 keV to several 100 keV, overlapping the CAPS-ELS range.

The survey described in this chapter takes into account injection events from SOI until the 17th June 2011, so five more years worth of data were considered, over a region between L = 3 and 13. We concentrate on young, large scale
injection events in the CAPS-ELS energy range that have concurrent increases or decreases in magnetic field strength. We also take into account data from other instruments.

The search concentrated on injection events within $L = 12$. An initial inspection was carried out by eye with survey plots of the CAPS-ELS data. Next we used an automated program looking specifically for changes in the magnetic field data and found a total of 60 injection events on 38 separate dates. Injection events with enhancements in magnetic field strength were of particular interest because Russell et al. [2006] reported these to be indicative of outward flowing plasma whereas studies such as André et al. [2007] deemed these events to be inward flowing. We hoped to test these opposing views of flow direction. Analyses were performed on each event, examining CAPS-ELS and IMS (ion mass spectrometer) data, magnetometer data from the MAG instrument, higher energy electron data from MIMI-LEMMS, and data from the Radio and Plasma Wave Science (RPWS) instrument where possible.

Specific questions that motivated our study are highlighted below.

1. The primary aim of the detailed analysis was to determine whether each event was made up of inward or outward flowing flux tubes. The successful determination of these radial flow directions would be valuable for establishing plasma circulation patterns in the kronian magnetosphere. We sought to test previous interpretations of these events and hoped to show a method with which the radial plasma flow direction of interchanging flux tubes can be determined. If it was possible to determine the flow direction of the event it was thought that it would then be possible to determine a
minimum velocity of the travelling flux tube. There has been evidence of a local time dependent current system in Saturn’s magnetosphere [M. Andriopoulou et al., Icarus, in preparation. 2012] and it would be interesting to know whether this is linked to the flow direction of these flux tubes.

2. We sought to investigate whether the magnetic field enhancements or depressions concurrent with the injection event are dependent on latitude [André, et al., 2007].

3. Using the newly found injection events we aimed to analyse the pitch angle distributions and how they develop before, during and after different types of injection events. We wanted to find out what pitch angle distributions can tell us about the direction of flow of the injection event, and to see whether a fresh injection starting with an isotropic distribution is a suitable assumption to make [Rymer, et al., 2008].

4. We sought to analyse the content of injected flux tubes in order to find out whether the plasma was an ambient plasma population or picked up from a neutral gas torus.

5. The interchange process suggests that the system should always be in pressure balance, so it would be interesting to calculate magnetic and plasma pressures inside and outside the flux tubes in order to see whether the plasma pressure increases when the magnetic pressure decreases, and vice versa.

It must be noted that the only conclusive method for finding the direction of motion of a flux tube is to determine the velocity of its plasma. Pitch angle distributions only give indications of motion based on assumptions regarding
initial pitch angle distributions. Magnetic field magnitude changes are also indirect indicators as it is assumed that the reasons for seeing such signatures is that cold plasma must be moving outwards and hot plasma inwards. If hot plasma is observed in a cold plasma environment the assumption is made that the cold dense plasma flux tube tends to move outwards due to centrifugal force, whereas the hot rarefied plasma is moving inwards in order to minimise potential energy. In reality these assumptions are well founded but the system is maybe more complex, as pressure gradients can also drive flux tube interchange, as described in section 5.1.1.

5.5 Plotting tools used for analysis

It is not possible to easily use the IMS moments time series to look for radial velocity components, or obtain the density or the pressure, when inside an injection event because the entire ion beam is not properly measured. Due to this fact we decided it was necessary to create a new method of analysing the data in order to attempt to see the radial components of motion and hence work out whether flux tubes were travelling in or out. A tool using plots as described in figure 57 was thus created by the CAPS-ELS Operations Manager, Dr. Gethyn Lewis, to enable our analysis.
Figure 57: a) an IMS energy-time spectrogram of all anodes summed, during a period when CAPS is directly viewing the corotation flow b) the change in CAPS actuator position in degrees during the same period; the sweep direction is highlighted as a red arrow. c) view of half of the sky as seen from Cassini, centred on the nominal direction from which the corotating thermal magnetospheric plasma is expected to arrive. Fluxes of ions at 512 eV together with their arrival direction are shown. The actuator sweep direction is indicated by the black arrow. The blue square in the centre indicates the nominal corotation direction. The blue triangle near the bottom shows the direction that the magnetic field is coming from and the blue dotted line across the middle of the circle is the plane perpendicular to the magnetic field. The black dotted line from top to bottom is the edge of the CAPS field of view. The small coloured circles across the middle indicate various moons. The black striped circle on the right hand side denotes Saturn. LEMMS is the Low Energy Magnetospheric Measurement System and HGA is the high gain antenna. These instruments are able to block electrons or ions that otherwise may be detected.
Figure 57a shows an IMS ion energy-time spectrogram of data from all 8 anodes summed, figure 57b the changing actuator angle with the red arrow showing the actuator sweep and figure 57c, the ion data from figure 57a for the actuator sweep in figure 57b at one energy bin (512 eV as this was the peak of the corotation beam) plotted in the field of view of the CAPS instrument. In figure 57c the data is plotted with the nominal direction of arrival of azimuthally flowing corotating plasma centred on the square in the middle of the plot, using corotation speeds from Wilson et al. [2008] and taking spacecraft motion into account. Plots such as that shown in figure 57c will be referred to as ‘corotation field of view plots’ (CFOV plots) herein. Figure 57c shows output from each individual anode, collated to show the complete coverage of that sweep. Each CFOV plot can plot one energy range; this particular one shows 512 eV in order to show the peak energy of the corotating ions.

The corotation speed is much higher than the ion thermal speed so the corotating ions all appear to arrive at the spacecraft from a small area of the sky and CAPS needs to observe the part of the sky centred on the corotation direction in order to see the full ion beam, including its thermal spread. This is not always possible to do as the spacecraft pointing may be dictated by the needs of other instruments. There is an amount of luck required in pointing in the corotation direction at the same time as an injection is taking place. Many injections are quite short so even if CAPS, in theory, can determine inward or outward flow, many events could have occurred before CAPS gets back to sweeping the area of the sky from which the ions may have been coming.
The assumption was made that, when inside an injection event flux tube, the direction of flow of ions will be the vector sum of the corotation (or subcorotation) flow and the radial motion of the interchanging flux tube. During a time when there are no radially moving flux tubes the flow should be centred about the nominal corotation direction. If the arrival direction of the flow is shifted closer to Saturn than corotation, in the field of view of CAPS, the flux tube is considered to be outward moving i.e. from Saturn towards the outer magnetosphere. If the flow is shifted further away from Saturn than corotation, in the field of view of CAPS, the flux tube is considered to be moving inwards. For the events which can be classified as having a radial velocity component, it is possible to estimate the speed of the flux tube using vector analysis, as shown in the cartoon in figure 58.

By looking at the data in this way it is possible to ‘see’ radial motion towards and away from Saturn, provided that the coverage of the sky around the corotation direction is sufficient. In order to determine radial flow directions, good coverage in the corotation flow direction and also of the direction radially in and out is ideally required. This coverage is controlled by the attitude of the Cassini orbiter. It was found that many events did not have sufficient coverage about the corotation flow direction to unambiguously determine radial flow directions.
Chapter 5: Injection events

Of 38 events in which there was an increase in the magnetic field direction coincident with an injection event, at 21 of them it was possible to make deductions about the direction of motion. The reasons it was not possible to analyse the others properly were either because CAPS was not actuating at the time or because there was not good enough spatial coverage in and around the corotation flow direction. The CFOV plotting tool uses the actuation of CAPS to build up a map of the arrival direction of electrons and ions at the spacecraft. Some of the more interesting events are described in the next section.
5.6 Case studies

Seven case studies are described in this section, each showing different characteristics and properties, which are summarized in table 3.
### Table 3: Summary table of the events used as case studies

<table>
<thead>
<tr>
<th>Date</th>
<th>Time (UT)</th>
<th>L shell</th>
<th>Latitude (°)</th>
<th>Local time</th>
<th>Increase or decrease in magnetic field strength</th>
<th>Calculated Age (hours)</th>
<th>Inferred direction of motion</th>
<th>Minimum inferred speed (km/s)</th>
<th>Additional information</th>
</tr>
</thead>
<tbody>
<tr>
<td>21st Mar 2006</td>
<td>07:40</td>
<td>8.5</td>
<td>0.3</td>
<td>19:56</td>
<td>Increase</td>
<td>0.259</td>
<td>Inward</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>10th Jan 2011</td>
<td>20:34</td>
<td>4.7</td>
<td>0.1</td>
<td>10:19</td>
<td>Increase</td>
<td>0.469</td>
<td>Inward</td>
<td>272</td>
<td>Have electron densities for this date.</td>
</tr>
<tr>
<td>24th Dec 2005</td>
<td>16:10</td>
<td>5.9</td>
<td>-0.2</td>
<td>14:29</td>
<td>Increase</td>
<td>1.97</td>
<td>Inward</td>
<td>153</td>
<td>Previously thought to be outward [Russell et al., 2006]</td>
</tr>
<tr>
<td>19th Dec 2007</td>
<td>20:41</td>
<td>10.9</td>
<td>-11.1</td>
<td>09:48</td>
<td>Increase</td>
<td>0.52</td>
<td>Inward</td>
<td>132</td>
<td>Birthplace of a bubble?</td>
</tr>
<tr>
<td>27th Aug 2009</td>
<td>04:10</td>
<td>6.1</td>
<td>-11.5</td>
<td>02:25</td>
<td>Decrease</td>
<td>2.171</td>
<td>Inward</td>
<td>78</td>
<td></td>
</tr>
<tr>
<td>28th Oct 2006</td>
<td>03:45</td>
<td>5.2</td>
<td>5.8</td>
<td>14:22</td>
<td>Both</td>
<td>1.4</td>
<td>Stationary</td>
<td>-</td>
<td>Previously thought to be outward [Burch et al., 2006]</td>
</tr>
<tr>
<td>28th Oct 2004</td>
<td>19:40</td>
<td>8</td>
<td>0.4</td>
<td>22:33</td>
<td>Both</td>
<td>0.552</td>
<td>Inward</td>
<td>214</td>
<td>Date used in André et al. [2007] to demonstrate latitudinal dependence of magnetic field strength variations</td>
</tr>
</tbody>
</table>

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Chapter 5: Injection events
5.6.1 21st March 2006

The event on the 21st of March 2006 shows a series of injection events with coincident increases in magnetic field strength. These events are equatorial and CFOV plots show that these events are travelling inward towards Saturn.

Figure 59a shows an energy-time spectrogram between 04:00 UT and 08:00 UT on this date, during which four clear injection events are observed, with the ion energy-time spectrogram shown in figure 59b. There are coincident enhancements in the magnetic field strength, shown in figure 59c. The events occur in the evening sector in local time, between L = 7 and 8.5. This local time would be consistent with reconnection generated injection events, as illustrated in figure 56.
If the magnetic field strength increases during the injection events it is reasonable to assume that the plasma pressure decreases. However it is not possible to accurately measure the electron pressure inside the injection events because the spacecraft potential is unknown during these events. The ion moments are also difficult to measure if most of the flux tube plasma is not detected.

Figure 59: a) An electron energy-time spectrogram for the four events on the 21\textsuperscript{st} March 2006 with anodes summed. b) An ion energy-time spectrogram with anodes summed for the same time period. c) Magnetic field strength for the same time period.
Chapter 5: Injection events

When the spacecraft is oriented such that the actuator sweeps the CAPS field of view across the corotation direction from a radially outward to a radially inward direction, plots such as figure 60 are convenient for testing whether the arrival direction of the ion beam has a radial component or is purely in the corotation direction. In figure 60 the horizontal blue line shows where the peak of the corotation beam occurs during each actuator sweep i.e. before and after the event. For the period surrounding this event it is at an actuator angle of 50°. The vertical blue lines show where the expected corotation beam lies.

Figure 60: Electron spectrogram, ion spectrogram and actuator angle for the flux tube at 04:30 UT. Blue vertical lines show the times at which the instrument is pointing into the plasma flow. Black lines show that during the injection event, the corotation flow beam is shifted towards a lower actuator angle. The blue horizontal line shows the actuation angle for the unperturbed flow.

When the spacecraft is oriented such that the actuator sweeps the CAPS field of view across the corotation direction from a radially outward to a radially inward direction, plots such as figure 60 are convenient for testing whether the arrival direction of the ion beam has a radial component or is purely in the corotation direction. In figure 60 the horizontal blue line shows where the peak of the corotation beam occurs during each actuator sweep i.e. before and after the event. For the period surrounding this event it is at an actuator angle of 50°. The vertical blue lines show where the expected corotation beam lies.
inside the injection event, the peak of the beam is instead at a lower actuator angle value, approximately 20°, as shown by the black lines, indicating that the beam is consistently shifted throughout the injection event. The black lines are fitted by eye. This is observed for each flux tube, demonstrating that the plasma in each injection event for this date is travelling in the same direction. However this type of analysis can only be carried out when the instrument is looking into the corotation flow so the actuator motion is able to swing the field of view to look towards or away from Saturn and ideally when the anode plane is perpendicular to the equatorial plane. Unfortunately this is not always the case, so the CFOV tool, which also tracks the sometimes important reorientation of the spacecraft during observations, is usually more useful for carrying out this type of analysis.

Figure 61 shows the ion data in the CFOV plots for one of the flux tubes during this event. The left hand CFOV plot is for a time when there is no injection event, shown at 1000 eV to catch the peak of the beam. It can be seen that the corotation flow seems to be arriving in the expected direction, where the square on the plot indicates the nominal corotation direction. The coverage of the CFOV plot is not ideal; a small region between the corotation direction and that away from Saturn has not been covered.
Figure 61: Two IMS CFOV plots associated with the flux tube at 07:40 UT on the 21st March 2006 placed above the electron spectrogram, the ion spectrogram and the actuator position plots. The left hand CFOV plot, at 1000 eV, is before the flux tube, the right hand CFOV plot, 10 keV, is during the flux tube. The latter plot shows higher energy ions to more clearly show their arrival directions. Arrows indicate where on the spectrogram these CFOV plots occur, blue rectangles indicate the temporal extent of the data shown in the CFOV plots.
When the CFOV plot covers a time during the injection event, as shown by the right hand CFOV plot in figure 61, the corotation flow beam is not apparent or observed at 10 keV. We infer this to mean the beam is likely to have been shifted into the region not covered by the field of view of CAPS because an outward moving beam would be detected between the blue square and Saturn. This could indicate a flux tube containing hot, inward flowing plasma travelling toward Saturn, i.e. an inward moving flux tube. Given the likely location of the beam in the hidden region, the minimum inferred radial inward velocity for this flux tube is 90 km/s.

5.6.2 10\textsuperscript{th} January 2011

The period of interest on the 10\textsuperscript{th} of January 2011 includes a series of injection events with coincident increases in magnetic field strength. These events occur near the equator and the CFOV plots are used to show that at least one of these events is travelling inward towards Saturn.

RPWS electron densities show that for at least half of the injection events during the time period there is a decrease in electron density at the same time as the increase in magnetic field strength, consistent with pressure balance being at least upheld to a degree.
Figure 62: a) An electron energy-time spectrogram for the 12 events on the 10th January 2011. b) An ion energy-time spectrogram for the same time period. c) Magnetic field strength for the same time period.

Figure 62a shows an energy-time spectrogram between 20:00 UT and 21:30 UT from this date, during which the injection events are clearly observed in the ion energy-time spectrogram shown in figure 62b. There are approximately 12 events during this time period, all with coincident enhancements in the magnetic field strength. The events occur in the morning sector in local time, at L ~ 4.5.

When viewed in the corotation field of view it can be seen that at least one of these injections is an inward moving flux tube. Figure 63 shows ion data CFOV plots, for a time when the data is ‘quiet’ i.e. when there is no injection event (left plot) and for a time inside the flux tube (right plot), at approximately 400...
It can be seen that the corotation flow seems to be arriving from the expected direction before the event, although the coverage is not as good as for the previous example. When viewed during an injection event at 20:34 UT the beam appears narrower, suggesting that the beam may have been shifted away from Saturn and that CAPS was only able to view a small portion of it. This would signify an inward flowing flux tube, but the coverage is not extensive enough to be certain. The minimum inferred velocity for this injection event is 272 km/s.
In order to determine whether the increases in magnetic field strength are due to the maintenance of pressure balance in the system, it was necessary to

Figure 63: Two CFOV plots associated with a flux tube on the 10\textsuperscript{th} January 2011 placed above the electron spectrogram, the ion spectrogram and the actuator position plots. The left hand CFOV plot, at 400 eV, is before the injection event, the right hand CFOV plot, also at 400 eV, is during the injection event. Arrows indicate where on the spectrogram these CFOV plots occur, blue rectangles indicate the extent of the CFOV plots.
calculate the plasma pressure inside the injection event. This is not possible to do using CAPS-ELS alone, primarily because the ion pressure is also required, but also because whilst inside an injection event the spacecraft potential value is unknown, making an estimate of the density difficult. An alternative is to use upper hybrid frequencies from the RPWS instrument in order to calculate the electron densities, as described in chapter 3. This is however, also difficult to do whilst inside an injection event as it is often not possible to find a strong upper hybrid frequency signal. For this case study it was possible for our collaborator to digitize six of the twelve events, and the electron number density is shown in figure 64.

Figure 64: Electron densities (bottom plot) during the event as calculated using RPWS data, compared to the electron spectrogram (top plot). Electron number densities calculated by Ann Persoon of the RPWS team.
As shown in the figure, the density within the injections consistently decreases relative to the ambient plasma, however some of the events contain much more dramatic density depletions than others. The ambient plasma density falls from approximately 120 to 80 cm$^{-3}$ and the flux tube densities from approximately 50 to 20 cm$^{-3}$; so the ratio between tube density and surrounding density is in the range half to a quarter. This data is qualitatively consistent with a pressure balance between the plasma pressure and the magnetic pressure over the course of the injection events. Pressure is proportional to density and temperature; lots of cold dense plasma has a relatively low pressure and hot plasma in the injection events might exert more pressure, but it is dependent on the amount of plasma. If total pressure is conserved, a jump up in magnetic pressure implies a drop in total pressure. That could happen if the ion and electron densities in the injected flux tubes are low enough despite the ions and electrons being hotter than the surrounding plasma. As such, densities alone cannot be used to make pressure estimates. Pressure balance could be valid here only if the temperature of the injection electrons was sufficient. This means that the RPWS seeing densities in the injected flux tubes that are, for example, one third that of the ambient plasma is not inconsistent with there being less plasma pressure in the flux tubes than the surroundings. This is true despite the fact that the spectrograms show lots of electrons across a range of energies and that the ion beams appear at higher energies. It is difficult to do further calculations because it is very rarely that we observe the full ion beam.
5.6.3 **24th December 2005**

The period of interest on the 24th of December 2005 shows a series of injection events with coincident increases in magnetic field strength. These events occur at the equator and the CFOV plots are used to show that one of these events is possibly travelling inward towards Saturn.

These events have been reported on previously by Russell et al. [2006] who believe that the increases in magnetic field strength are indicative of a decrease in plasma pressure and that the injection events are therefore moving outward. Our results differ from this conclusion.
Figure 65: a) An electron energy-time spectrogram for the events on the 24th December 2005. b) An ion energy-time spectrogram for the same time period. c) Magnetic field strength for the same time period.

Figure 65a shows an energy-time spectrogram between 16:00 UT and 16:40 UT on this date, during which it is clear to see injection events occurring, with the ion energy-time spectrogram shown in figure 65b. There are coincident enhancements in the magnetic field strength, shown in figure 65c. The event occurs in the afternoon sector in local time, at L = 5.6. Figure 66 shows the ion data as CFOV plots during and after the injection event. It can be seen that the corotation flow seems to be arriving from the expected direction during the latter time, however when viewed during the injection event at 16:11 UT the beam is shifted away from Saturn. There is a slight trace of ions arriving from the near corotation direction but the peak of the beam is believed to be shifted
out of the field of view. This would signify an inward flowing flux tube, which is opposite to the direction inferred by Russell et al. [2006]. We can rule out outward motion because it is possible to see all the way from the blue square to Saturn. The minimum inferred radial velocity for this flux tube is 150 km/s.
Figure 66: Two IMS CFOV plots associated with the injection events on the 24th December 2005 placed above the electron spectrogram, the ion spectrogram and the actuator position plots. The left hand CFOV plot is during the injection and the right hand CFOV plot is after the injection, both are at 512 eV. Arrows indicate where on the spectrogram these CFOV plots occur, blue rectangles indicate the extent of the data shown in the CFOV plots.
5.6.4 19th December 2007

The 19th of December 2007 period shows a series of injection events with coincident increases in magnetic field strength. These events occur away from the equator and the CFOV plots are used to show that these events are probably travelling inward towards Saturn.

These events are of particular interest because they go against the hypothesis of André et al. [2007] that increases in magnetic field strength are seen at the equator and decreases in magnetic field strength are seen away from the equator. Here we have an example of an increase in magnetic field strength away from the equator, at a latitude of -11°.
Figure 67 shows an energy-time spectrogram covering 19:50 UT to 22:20 UT on this date, during which there are four injection events, with the ion energy-time spectrogram shown in figure 67b. There are coincident enhancements in the magnetic field strength, shown in figure 67c. These injections differ from ones discussed previously because of the depletions in the low energy electrons, between 10 and 100 eV, and they seem to be unusually long lived. The events occur in the morning sector in local time and occur at L = 10.5, which are some of the furthest events from Saturn observed in this study.
Figure 68: Two CFOV plots associated with the injection event on the 19th December 2007 placed above the electron spectrogram, the ion spectrogram and the actuator position plots. The left hand CFOV plot (at 512 eV) is before the injection event and the right hand CFOV plot (at 724 eV) is during the injection event. Arrows indicate where on the spectrogram these CFOV plots occur, blue rectangles indicate the extent of the CFOV plots. In the CFOV plot that is inside the flux tube, there are field aligned ion features. These are light blue, one is visible over a blue triangle which indicates the +B field aligned direction.

Figure 68 shows CFOV plots before and during the injection event. Before the flux tube it can be seen that the corotation flow seems to be arriving from the expected direction although the coverage does not quite extend to the nominal
corotation direction. During the injection event the beam is not observed, suggesting that the beam may have been shifted away from Saturn, out of the field of view. This would signify an inward flowing flux tube. During the injection event there appears to be a field aligned ion feature, which is consistent with the features of a magnetic bubble [Birn, et al., 2004]. The minimum inferred velocity of each of these events varies between 110 and 130 km/s.

5.6.5 27th August 2009

On the 27th of August 2009, a series of injection events occurred with coincident decreases in magnetic field strength. These events occur away from the equator and the CFOV plots are used to show that these injections are probably travelling inward towards Saturn.
Figure 69: a) An electron energy-time spectrogram for the events on the 27\textsuperscript{th} August 2009. b) An ion energy-time spectrogram. c) Magnetic field strength.

Figure 69a shows an energy-time spectrogram between 04:00 UT and 05:00 UT on this date, during which there are three large injection events. The event occurs in the early morning sector in local time, at $L = 5.8$ and at a latitude of $-11.8^\circ$.

An interpretation of the spectrograms with respect to actuator angle is more difficult for this event as the beam is difficult to discern, but it appears that inside each injection event the beam moves to the more positive actuator angle, i.e. away from Saturn in this context. This is demonstrated in figure 70.
Figure 70: showing the electron spectrogram, ion spectrogram and actuator sweep angle for the flux tubes during this event. Blue vertical lines show the times when the peak flux was observed in the corotation flow. Black vertical lines show that during the injection events, the corotation flow beam is shifted towards a more positive actuator angle. The horizontal blue line shows that the actuator crosses the unperturbed beam at -10°.
Chapter 5: Injection events

Figure 71 shows the ion data in the CFOV plot for a time when the data is ‘quiet’ and CFOV plots during each of the flux tubes. It can be seen that the corotation flow seems to be arriving from the expected direction although coverage of only half the hemisphere centred on the corotation beam is available. As we can see all the way between the blue square and Saturn we can rule out outward motion. When viewed during the injection events the beam is not observed, suggesting that the beam may have been shifted away from Saturn out of the field of view. This would signify inward flowing flux tubes.

Figure 71: four CFOV plots showing how the beam is apparent during quiet times (first plot), but is not apparent during each of the flux tubes, placed above the electron spectrogram, the ion spectrogram and the actuator position plots. Arrows indicate where on the spectrogram these CFOV plots occur, blue rectangles indicate the extent of the CFOV plots. All CFOV plots are at 512 eV.
5.6.6  28TH OCTOBER 2006

The events on the 28th October 2006 show a series of injection events with both increases and decreases in magnetic field strength. These events occur away from the equator and the CFOV plots are used to show that these events are probably travelling inward towards Saturn.

This event is interesting because it shows that both increases and decreases in magnetic field strength can be associated with a location away from the equator, contrary to that stated by André et al. [2007].

![Image](image.png)

Figure 72: a) An electron energy-time spectrogram for the events on the 28th October 2006. b) An ion energy-time spectrogram. c) Magnetic field strength.
Figure 72a shows an energy-time spectrogram between 03:40 UT and 04:10 UT from this date, during which there are three large injection events and some smaller ones, with the ion energy-time spectrogram shown in figure 72b. There are coincident decreases in the magnetic field strength for all injections except for one injection at 03:44 UT which has an increase, shown in figure 72c. The event occurs between 14:00 and 14:30 LT, L = 5.2 and spacecraft latitude increases from 4° and 8°. During the event the equator is not crossed so it is interesting that both increases and decreases are observed. Of particular interest with this event is that during the large injection the cold ion population disappears and only ions above 1 keV remain.
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Figure 73 shows the ion data in the CFOV plot for a time when the data is both 'quiet' and disturbed. It can be seen that the corotation flow seems to be arriving from the expected direction although there is only half the coverage of the nominal flow direction is available. When viewed during the injection event...
at 04:00 UT (the only one for which CAPS coverage coincided with the nominal corotation flow direction) the beam appears not to move although the flux is lower, demonstrating that the injection event could be stationary when encountered, or perhaps the beam has shifted slightly so less of it can be observed. We note that within the injection event, the lower-energy portion of the ion beam is apparently missing.

5.6.7 28\textsuperscript{th} October 2004

On the 28\textsuperscript{th} October 2004 two different sets of injection events are presented, one around 07:30 UT and the other around 19:00 UT. The set that begin at 07:30 UT show decreases in magnetic field strength, occur away from the equator and show events that are either stationary or inward.

The set that begin at 19:00 UT show increases in magnetic field strength, occur close to the equator and the CFOV plots are used to show that some events are possibly travelling inward. André et al. [2007] claim that all injection events on this date (including both sets described here) are inward moving regardless of their variable magnetic field strength, using the latitudinal dependence as a reason for the changing magnetic field strength, based on the theoretical interpretation that plasma depleted flux tubes are most likely to travel inwards in a rotation dominated magnetosphere.

The injection event at approximately 19:00 UT is shown by our methods to be flowing inward, but was deemed by Burch et al. [2007] to be outward flowing. Burch et al. use the butterfly pitch angle distributions of some of the injection
events on this date to justify their hypothesis that the plasma is being transported outward from source locations at the icy moons Dione and Tethys.

These events are different to those on the 28th October 2006 because whilst both type of injection event are present, they are separated by some hours, and increases in magnetic field strength are observed close to the equator whilst decreases are observed away from the equator.

Figure 74: a) An electron energy-time spectrogram for the events on the 28th October 2004. b) An ion energy-time spectrogram. c) Magnetic field strength.

Figure 74a shows an energy-time spectrogram covering a time from 07:30 UT to 08:20 UT, during which there is one big injection event and many other smaller ones, with the ion energy-time spectrogram shown in figure 74b. There are decreases in the magnetic field strength when the hot electrons are
observed, during every injection event, shown in figure 74c. The larger event occurs at 07:55 LT, L = 6.3, when Cassini’s latitude is 13.5° North.

Analysis of the spectrograms with respect to actuator angle, as shown in figure 75, could indicate a stationary injection event, if the data artefact at 07:53 UT is ignored. With this type of analysis it is hard to be sure if the beam is stationary or not because the actuator is almost at the limit of 100° when the sensor sees the corotating beam. It is possible that the beam is fainter during the injection event because the peak is beyond the scope of the actuator. This type of analysis is therefore reinforced by using the CFOV plots as well.
Figure 75: showing the electron spectrogram, ion spectrogram and actuator sweep angle for the flux tubes during this event. Blue vertical lines show the corotation flow direction, at an actuator angle of 100°. All beams appear to arrive from this direction, indicating a stationary flux tube.
Figure 76: Two CFOV plots during the 28th October 2004, above the electron spectrogram, the ion spectrogram and the actuator angle sweep, for injections during which there were decreases in the magnetic field strength. The first plot is during the injection event, the second plot is during a quiet time, and both are at 430 eV. Arrows indicate where on the spectrogram these CFOV plots correspond to, blue rectangles indicate the extent of the CFOV plots. The coverage between the two plots differs because the time span is limited in the left hand plot due to the data gaps.
Figure 76 shows the ion data in the CFOV plots during and after one of the injection events. It can be seen that the corotation flow seems to be arriving from the expected direction although there is only half of the ideal coverage available. When viewed during the injection event the beam appears to be closer to Saturn, demonstrating that the injection event could be outward flowing. However, there are some caveats because at this same time there are data gaps and an instrument mode change in between 07:50 and 07:58 UT, making a direct comparison of some portions of data challenging. If the data artefact immediately following the mode change is ignored, it is more likely that this event is actually stationary. However, it is difficult to know for sure because the ion peak is not visible and actually may have shifted outside of the field of view. If this is the case then it could be possible that the injection event is an inward flowing flux tube.

Later on in the same day there are injection events coincident with magnetic field strength enhancements. Figure 77a shows an energy-time spectrogram between 18:40 UT and 19:40 UT from this date, during which there are many injection events, with the ion energy-time spectrogram shown in figure 77b. There are increases in the magnetic field strength at every injection event, shown in figure 77c. The events occur between 22:14 and 22:33 LT, L = 7.7 to 8 and all events are very close to the equator, in contrast to events earlier in the day.
Figure 78 shows the ion data in the CFOV plot both during an injection event and for a time when the plasma flow is unperturbed. It can be seen that the corotation flow seems to be arriving from the expected direction although CAPS coverage is limited to half of the corotation-centered hemisphere. When viewed during an injection event at 19:02 UT the beam is not apparent and has been shifted outside the field of view of the plot, demonstrating that the injection event could be inward flowing.
In this section we have shown various case studies of injection events in the survey and explained the analyses and conclusions drawn from the use of the survey.

Figure 78: Two CFOV plots during the 28th October 2004, above the electron spectrogram, the ion spectrogram and the actuator angle position. The first plot is during the injection event at 1100 eV, the second plot is during a quiet time at 700 eV. Arrows indicate when on the spectrogram these CFOV plots cover; blue rectangles indicate the extent of the CFOV plots.

5.6.8 **Summary of case studies**

In this section we have shown various case studies of injection events in the survey and explained the analyses and conclusions drawn from the use of the survey.
CFOV plots and other methods. Of the 7 case studies, four are equatorial and three are not, four show increases in magnetic field strength, one shows decreases and two show both increase and decreases. The latitudinal dependence of the magnetic perturbation is as André et al. [2007] suggested, but there seem to be some interesting exceptions.

The CFOV plots were useful in the analysis of the direction of motion of the injection events; all seven could be inward flowing flux tubes although one could be stationary. We were able to infer the speeds for 6 of the events and calculated speeds between 78 and 272 km/s. With these inferred speeds, and the duration of each event measurable, it was possible to calculate some approximate radial sizes of the events. These events vary between 10,000 km and 90,000 km.

5.6.9 Case studies of pitch angle distributions

In order to investigate the pitch angle distribution development during adiabatic transport, as described in Rymer et al. [2008] we analysed many events in terms of their pitch angle distributions before, during and after the injection. The results for some of the events are shown here, separated into cases near the equator and cases away from the equator.

5.6.9.1 Equatorial events

Pitch angle distribution plots are shown in figure 79 for various times and energy ranges before, during and after the injection event at 07:38 UT on the
30th October 2005. The same event was analysed, therefore similar plots are shown, in Rymer et al. [2008] and as such it is treated as a ‘textbook example’ in this case. Before and after the injection there are slightly field aligned distributions at low energies and butterfly distributions at middle energies. Before the injection event there is a pancake distribution at high energies, but after the injection there is a butterfly distribution at high energies. The pancake distribution before the injection event could be indicative of a smaller, fresh injection event occurring at that time hence the observation of isotropic plasma being transported inwards.

The butterfly distributions are observed because the plasma before and after the injection event is spotted with many smaller injection events. Hence, the butterfly distributions indicate electrons drifting out of previous injections. Inside the injection event there are field aligned distributions at energies less than 500 eV and pancake distributions at 10 keV. However at 1 keV there is a butterfly distribution. It is possible that at around 1 keV inside the injection event, the plasma measured has dispersed out of a previous flux tube, hence the presence of the butterfly distribution.
Figure 79: Pitch angle distributions before, during and after the flux tube at 07:38 UT on the 30th October 2005, for various energies and times as labelled. Field aligned, pancake and butterfly distributions were all observed.
Pitch angle distribution plots are shown in figure 80 for various times and energy ranges during the injection event on the 21st March 2006 at 04:30 UT. Before and after the flux tube mostly isotropic distributions are seen, particularly for high and low energy electrons. For electrons with energies around 500 eV a butterfly distribution is seen. The butterfly distribution before the injection event, plot 2 in figure 80, could indicate that these electrons were part of a previous injection event, but have dispersed out of the injected flux tube i.e. as a pancake distribution that was transported outward [Rymer, et al., 2008]. The butterfly distribution after the injection event, plot 9 in figure 80, could indicate that these electrons were part of the injection event as shown in figure 80 but have dispersed out of the injected flux tube. Inside the flux tube at energies below 1 keV distributions are field aligned. These lower energy electrons cannot come from the outer magnetosphere or they would have higher energies. It has been proposed that this field aligned distribution is a signature of the interchanging flux tube being connected to the ionosphere [Rymer, et al., 2008]. It is possible that electric fields are set up as the flux tube moves inward, due to the footprint of the flux tube in the ionosphere also moving. Thus field aligned currents can flow and the current carrying electrons are observed in the field aligned pitch angle distribution.
Figure 80: The pitch angle distributions before, during and after the injection event at 04:30 UT on the 21st March 2006, for various energies and times as labelled. Field aligned (e.g. 5,6), pancake(e.g. 4), isotropic (e.g. 3) and butterfly (e.g. 2,9) distributions were all observed.
Chapter 5: Injection events

The hot electrons in the flux tube show a pancake distribution, such as plot 4 in figure 80, indicating the inward motion of an isotropic distribution, which is expected for hot electrons in an injection event.

Pitch angle distribution plots are shown in figure 81 for various times and energy ranges during the injection event at 07:40 UT on the 21st March 2006. Before and after the injection event, for electrons under 1000 eV, we see field aligned distributions, indicating outward transport of an isotropic distribution.

It is worth noting here that the ambient plasma is probably much the same as the ambient plasma in figure 80 but the data is from a larger L shell location and at a slightly different local time, so it is not necessarily surprising that a field aligned distribution is observed.

At energies around 5 keV butterfly distributions are present. This is consistent with the idea that electrons have drifted out of earlier injections.

Inside the injection event at energies less than 1 keV there are field aligned distributions, again possibly indicating a signature of the interchanging flux tube being connected to the ionosphere. At higher energies, over 10 keV, we see new butterfly distributions. The butterfly distribution in the injection event is a feature not reported before by Rymer et al. [2008].

At the top (high energy end) of an injected flux tube we expect to see a pancake distribution. However, the top of this injection event is in the MIMI-LEMMS range and we cannot measure the pitch angle distribution of this flux tube at higher energies because the instrument stopped actuating in February 2005 and this event is in 2006, thus no pitch angle data at higher energies is available.
The butterfly distribution could also indicate that we are measuring the
dispersion of electrons out of a previous flux tube. Or the butterfly distribution
could be due to plasma in the near vicinity of dust, causing the previously
pancake distribution to evolve into a butterfly distribution [Burch, et al., 2007].
If the butterfly distribution started as an isotropic distribution it is unclear
what transport is taking place, as this is a new feature in the pitch angle
analysis.

It is interesting that for this event no isotropic distributions are observed, as
they would be expected before and after the injection event if we were making
the same assumptions about isotropy as set out by Rymer et al. [2008].
Figure 81: showing the pitch angle distributions before, during and after the fourth injection event, for various energies and times as labelled. Field aligned (e.g. 2, 3, 5, 6, 8, 9), and butterfly distributions (e.g. 1, 4, 7) were observed.
5.6.9.2 Non equatorial events

Pitch angle distributions for the flux tube at 21:50 UT on the 19th December 2007 are shown in figure 82. Before and after the injection event low energy electrons display a weakly field aligned distribution but at higher energies isotropic distributions are observed. Just inside the injection event the low energies have field aligned pitch angle distributions and high energies have isotropic distributions. Later on inside the injection event the distributions are field aligned at all energies, either indicating outward moving plasma or the ionospheric coupling mentioned previously. This event is interesting as there is no evidence of pancake or butterfly distributions at all. It is possible that this is indicative of a fresh injection event that has not yet had time to disperse; hence most of the pitch angle distributions are isotropic. This is based on the assumption by Rymer et al. [2008] that plasma distributions are initially isotropic.
Chapter 5: Injection events

Pitch angle distributions for the flux tube at 04:30 UT on the 27th August 2009 are shown in figure 83. Before and after the injection event low energy electrons display an isotropic distribution but at higher energies butterfly distributions are observed. This makes sense due to the presence of dispersions at these higher energies.

Inside the injection event the low energies give rise to field aligned pitch angle distributions and high energies give rise to pancake distributions, as expected. In plot 6 of this figure it is possible that another electron population is
observed, perhaps if the spacecraft passed through different types of plasma while accumulating the data in this pitch angle distribution. This would explain the points on plot 6 that are not isotropic.
Figure 83: Pitch angle distributions before, during and after the injection event at 04:30 UT on the 27th August 2009, for various energies and times as labelled. Field aligned, pancake, butterfly and isotropic distributions were all observed. The pitch angle coverage was not complete, so a portion of the distribution is missing.
Figure 84 shows pitch angle distributions for the flux tube at 04:00 UT on the 28th October 2006. Before and after the injection event all of the electron pitch angle distributions display an isotropic distribution. It is interesting to see that in some cases there is evidence of two populations of electrons, with different $D_EDF$, but each is still isotropic.

Inside the injection event the low energies have isotropic pitch angle distributions and high energies have pancake distributions, indicating the inward transport of the flux tube. In this case study there is no evidence of a field aligned population.
Figure 84: The pitch angle distributions before, during and after the flux tube at 04:00 UT on the 28th October 2006, for various energies and times as labelled. Pancake and isotropic distributions were observed. The double signatures in the plots after the injection (11-15) could be due to sampling some of the injection PAD as well as the PAD for the time after the event.
5.6.9.3 Summary of pitch angle distributions

The pitch angle analyses in this section were undertaken with the model created by Rymer et al. [2008] in mind. Using their assumptions of adiabatic transport and the populations being initially isotropic, we observe a set of case studies that appear to fit the Rymer et al. model on some occasions. A summary is shown in Table 4.

<table>
<thead>
<tr>
<th>Date (dd/mm/yy)</th>
<th>L shell</th>
<th>Latitude (°)</th>
<th>Local time (hours)</th>
<th>Observations outside injection event</th>
<th>Observations inside injection event</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>30/10/2005</td>
<td>7</td>
<td>0.4</td>
<td>23:13</td>
<td>Field aligned, pancake and butterfly</td>
<td>Field aligned, pancake and butterfly</td>
<td>No evidence of isotropic</td>
</tr>
<tr>
<td>Equatorial</td>
<td>21/03/2006</td>
<td>7.3</td>
<td>0.2</td>
<td>19:00</td>
<td>Isotropic and butterfly</td>
<td>No evidence of isotropic</td>
</tr>
<tr>
<td>8.5</td>
<td>0.3</td>
<td>19:56</td>
<td>Field aligned and butterfly</td>
<td>Field aligned and butterfly</td>
<td>No evidence of isotropic or pancake or butterfly</td>
<td></td>
</tr>
<tr>
<td>19/12/2007</td>
<td>11.1</td>
<td>-10.5</td>
<td>09:57</td>
<td>Isotropic and field aligned</td>
<td>Isotropic and field aligned</td>
<td>No evidence of isotropic or pancake or butterfly</td>
</tr>
<tr>
<td>Non equatorial</td>
<td>27/09/2009</td>
<td>6.0</td>
<td>-11.6</td>
<td>02:34</td>
<td>Isotropic and butterfly</td>
<td>No evidence of field aligned or butterfly</td>
</tr>
<tr>
<td>28/10/2006</td>
<td>5.3</td>
<td>6.6</td>
<td>14:29</td>
<td>Isotropic</td>
<td>Isotropic and pancake</td>
<td>No evidence of field aligned or butterfly</td>
</tr>
</tbody>
</table>

Table 4: A summary of the pitch angle distribution analyses for the case studies shown in this section.

Equatorial events gave mixed results. Most of the distributions observed for the three equatorial case studies could be explained using the model from Rymer et al. [2008] but there were some occasions in which the pitch angle distributions did not make sense or were not observed when expected in the context of adiabatic transport.
The first event on the 21st March 2006 gives an assumed ‘textbook’ set of pitch angle distributions. The isotropic and butterfly PADs before and after the event and the field aligned and pancake PADs during the event can be explained using the Rymer et al. model.

The second event on the 21st March 2006 gives field aligned and butterfly distributions before, after and during the injection event. It is interesting to note that for this event there are no isotropic distributions.

The event on the 30th October 2005 did not shown any isotropic distributions before or after the flux tube, but this could be because the 40 minute data set that was analysed was interspersed with many small injection events, hence even the plasma before and after the main injection event has been transported somewhat.

Non equatorial events also gave mixed results. Isotropic distributions were observed more often for non equatorial events than for equatorial ones.

The event on the 28th October 2006 was interesting because it did not show evidence of field aligned or butterfly distributions, particularly inside the injection event where field aligned distributions have been observed previously.

The most interesting case here is that of the 19th December 2007 for which the pitch angles distributions are mostly isotropic before, during and after the injection event. This could indicate a fresh, new injection before anything has had the time to disperse, i.e. Cassini encountered this injection at its inception.
The Rymer et al. [2008] PAD model cannot be used to explain every scenario. We have reported on distributions observed at unexpected locations, which demonstrates that perhaps the pitch angle analysis is more complex than previously thought.

5.7 Results of the survey
5.7.1 Magnetic field and latitudinal dependence

The various injection events that were found in the entire Cassini dataset to date can be organised into specific groups, from which some patterns can be ascertained. The first subdivision is between injection events with increases or decreases in magnetic field strength compared to the surroundings. These two categories can be further split into those that are equatorial and non-equatorial. In total there are 22 events with enhanced magnetic field strength injections, of which only two events are non-equatorial, at a latitude of -11°. In total there are 10 dates with decreases in magnetic field strength, none of which are equatorial. This does appear to fit with the hypothesis that the difference in magnetic field strength between an injected flux tube and its surrounding is dependent on latitude [André, et al., 2007]. At high latitudes the plasma has higher temperatures, which leads to an increased plasma pressure; hence a decrease in magnetic field strength is required to maintain the pressure balance. Figure 85 shows a histogram of the events organised by latitude and change in magnetic field strength fluctuation direction. The frequency is normalised by the amount of time Cassini spent at each particular latitude, within our L shell range.
The majority of ‘increases’ collect around the equator whereas the ‘decreases’ are spread in latitude away from the equator. There were no observed events at latitudes greater than 15° or less than -35° although Cassini has visited those locations. Once normalised, the number of decreasing field cases gave a stronger peaks away from the equator when compared to the number of increasing field cases about the equator.

The strongest outliers in figure 85 are the magnetic field increases that do not lie about the equator but are observed in the -20° to -10° bin. Interestingly these belong to the event on the 19th December 2007 so it seems that the events on this date are different to other injection events in terms of the relationship between pitch angle distribution and magnetic latitude.

![Figure 85: Histograms of the latitudinal dependence of the injection events, organised by increases or decreases in magnetic field strength. The off equator increases are all from the event on the 19th December 2007.](image-url)
5.7.2 Local time dependence, L shells and ages

Figure 86 shows a histogram showing the local time dependence of all the injection events at the local time of observation, normalised by the amount of time spent by Cassini at those locations. There appears to be a preference for injection events to be close to local midnight and local noon and a peak between 18.00 LT and 21.00 LT.

Figure 87 shows a plot of L shell against local time of the injections in this survey, with the Cassini trajectory over plotted as a dashed line. There are two main populations of injections, one in the late evening to early morning sector (20:00 – 02:00 LT), and one between 10:00 and 15:00 LT. Injection events found further out thus far tend to cluster around 10:00 LT. It is interesting to note that these are also the events on the 19th December 2007, so now we see
that this event is unusual in pitch angle distribution, distribution of magnetic
perturbation with magnetic latitude and L shell.

![Diagram of L shell against local time]

**Figure 87**: Injection event distribution in L shell and local time. Events from the
19th December 2007 are circled in blue.

Figure 88 shows a plot of ages (as derived using the Hill et al. [2005] equation)
against local time, with error bars showing minimum and maximum possible
ages. There appears to be two populations of injections, one in the late evening
to early morning sector, and one between 10:00 and 15:00 LT. The oldest
injections tend to be between 10:00 and 15:00 LT. There are 13 events which
are younger than 0.5 hours, including the events from the 19th December 2007,
circled in blue. In this plot the events on the 19th of December do not stand out
in the same way as they have done previously. However, when compared to the
other events with similar ages the December events are still very different. Of the 13 young events, all except the 19th December events and some on the 27th August 2009 have increases in magnetic field strength and are found around the equator. One injection event on the 27th August is very young, but is found away from the equator at $-11.8^\circ$, and shows a decrease in magnetic field strength. This decrease is expected if the hypotheses by André et al. [2007] are proven to be correct. The events on the 19th of December 2007 are some of the youngest, the only ones found with increases in magnetic field strength away from the equator, and the ones with the most intriguing pitch angle distributions.

Figure 88: Minimum inferred ages of the injection events against local time. Events from the 19th December 2007 event are circled in blue.
Table 7, table 8, table 9 and table 10 in Appendix B summarise all the events in terms of their main characteristics.

The injection events investigated in this survey were plotted in terms of local time and their flow direction, but it was difficult to ascertain a local time relationship with so few clear events to investigate, therefore it was difficult to investigate the effect of the recently-discovered local time dependent current systems [M. Andriopoulou et al., Icarus, in preparation. 2012].

It is possible to calculate the local time of the injection source from the local time of observation [Chen & Hill, 2008] using the angular velocity and the injection time. This was carried out for the injection events in this survey and results are shown in figure 89. It would appear that the majority of our injection events come from between 06:00 LT – 15:00 LT on the dayside, 18:00 LT – 21:00 LT on the nightside and between midnight and 03:00 LT. The nightside occurrences concur with findings by Müller et al. [2011] who find source locations between 21:00 LT – 03:00 LT. We see a similar peak, but also a peak around midday. However, Müller et al. do not explicitly say how the source locations were calculated, so it is impossible to directly compare results.

It is interesting that we potentially observe two sets of injection events at their source locations (one around midday and one around midnight). This could be indicative of two types of injection events being created; some due to reconnection in the tail and some due to centrifugal interchange instabilities and movement of the magnetopause.
Figure 89: Histogram showing the inferred local time at the source of the injection events, normalised by the amount of time Cassini spent at those locations, for the L shell range used in the survey.
5.7.3 Velocities

Speeds were calculated to be quite high, predominantly between 100 and 200 km/s. These values agree with a model by Wilson [private communication] which give calculated velocities within ±10 km/s of the values inferred using the velocity triangles, and work by Paranicas [private communication] and Rymer et al. [2008] who mention velocities between 89 and 260 km/s.

The minimum inferred velocities were plotted against local time of observation but there did not appear to be a correlation. Some of the younger injection events appear to have higher minimum inferred velocities, as shown in figure 90.

A calculation using the minimum inferred velocity and the age of each event was used to estimate the approximate possible distances travelled by the injected flux tubes in the unlikely, extreme cases where they moved with a constant radial speed. The analysis was only an exercise to gauge the range of distances over which injections could travel radially, if they did move with constant speeds, and it is likely that injections have varying radial speeds.
This data was extrapolated to estimate the source locations of these injection events, assuming radial transport and no braking/speeding up, and assuming that all the injection events were inward flowing and hence would have started out further from Saturn. The results are shown in figure 91, with the observed locations in blue and the inferred source locations in red. It is interesting to note that there are two main groups in the inferred source locations; one between \( L = 6 \) and 18 and the other between \( L = 22 \) and 28. This could indicate that the inward flowing flux tubes arrive either from the plasma sheet in the inner magnetosphere, or from the outer magnetosphere near Titan’s orbit. This hypothesis needs to be examined further, but was decided to be outside of the scope of this thesis.
5.7.4 **Pick up energies**

The content of the injected flux tubes does not seem to be picked up plasma because the energies of the injection events are generally higher than that of calculated pick up energies at the inferred locations of the injection events in this survey. A graph of the ion pickup energy against L shell is shown in figure 92 and it can be seen that at L = 28 the energy could reach more than 400 eV but most of the injection events in the survey reach energies up to the maximum of the ELS instrument. In some instances it has been suggested that electrons are heated to ion corotation (pick up) energies by Coulomb collisions as the electrons are transported outward [Rymer, et al., 2008]. It could be possible that some of the content is due to plasma pickup, but the higher
energy plasma is very likely to be plasma migrating inwards from the outer magnetosphere.

![Figure 92: How the pickup energy for one proton varies with distance from Saturn, based on corotation speeds from Wilson et al. [2008].](image)

**5.8 Discussions and Conclusions**

Analysis of the corotation flow direction of injection events has provided a new method to observe the direction of the interchanging flux tubes, a technique that has not previously been investigated. The method has proven successful; a number of inward moving flux tubes were noted for a number of different events, addressing the first of the motives in section 5.4. However, there are limitations with the method in that during the event the actuator has to be sweeping across a particular region of the sky as seen from Cassini, otherwise
the event cannot be analysed. On at least six events the coverage was not wide enough to accurately analyse the data.

Outward flowing flux tubes have not yet confidently been observed using the new method, which is important, because determining the presence of outward flowing flux tubes has also proven difficult with other techniques. However, two events that have previously been reported as outward-flowing have now been interpreted to be inward flowing or stationary using the CFOV plots [Burch, et al., 2007; Russell, et al., 2006].

Increasing magnetic field strength events tend to be observed very near the equator and decreasing magnetic field strength events tend to be observed away from the equator, addressing the second motive in section 5.4. This is attributed to the requirement for injection events to remain in pressure balance even at higher latitudes where plasma has higher temperatures. This leads to an increased plasma pressure and hence a decrease in magnetic pressure is required to maintain the pressure balance. Perhaps cold plasma is trapped about the equator. Our most interesting case is that of the 19th December 2007 in which we see increases in magnetic field strength away from the equator. Perhaps the 19th December case is one in which plasma has been lost and hence the pressure is reduced, but because the flux tube has not yet moved inwards and has not become more dipolarised, even at higher latitudes its pressure is less than the surroundings. This could be a simple way of explaining why the field increases in both polar and equatorial locations for this case.
Reconnection and the Vasyliunas cycle is unlikely to be the cause of many of the injection events, because at least half are found in the dayside magnetosphere (such as the case study on the 19th December 2007). As the Vasyliunas cycle’s effects are only expected to be easily observable on the nightside, this could mean it is possible that the injections are dependent instead on the solar wind. Perhaps the solar wind pressure increases sufficiently to affect the plasmoids that cause the injection events.

5.8.1 Plasma flow models

All the analysed events have ages less than ten hours old, indicating relatively fresh injections of plasma, and those that are clearly determined to be moving were calculated to have speeds in the region of 100 – 200 km/s.

It has been interesting to find that some of the injection events appear to be stationary. We hypothesize that this could mean that either they are created at that location, or they move inward and then disperse out of the injected flux tube, onto the surrounding, gradually out flowing flux tubes and are carried out to the tail. Such a circulation pattern was mentioned by Rymer et al. [2008]. We believe, however, that a more reasonable interpretation is that of magnetic bubbles rather than ‘fingers’, similar to those bubbles observed at Earth. The magnetic field signatures for magnetic bubbles at Earth were simulated by Birn et al. [2004] and the enhancements and decreases of B that we observe in this study do agree qualitatively with the signatures described in their simulations. The propagation and early evolution of a bubble at Earth has been modelled in the form of a pressure balanced, depleted flux tube that has an equatorial
magnetic field which is greater than the magnetic field of the surroundings. Within the flux tube there was a sudden reduction of pressure, dominated by the requirement to re-establish the total pressure balance. This reduction of pressure at Earth has been shown to occur mainly in the dawn-dusk and north-south directions. The pressure balance is restored by a compressional feature in the magnetic field, which is also observed for many of the injection events presented in this chapter. This compression leads to earthward propagation of a magnetic bubble at speeds of the order of 200 – 400 km/s [Birn, et al., 2004]. These earthward bubbles are also associated with field aligned current systems; some of the injection events in this chapter have field aligned features, such as the field aligned beams observed during the 19th November 2007 event.

The kronian system is different to the terrestrial one, so whilst the findings in Birn et al. [2004] are interesting, those results cannot be directly compared with the results of this survey. However it does provide some insights into bubble evolution and pressure balance within the magnetosphere and, as a future project, there is scope for further analysis of these sorts of bubbles at Saturn, which, in time, would address the fifth motive in section 5.4.

The re-analysis of previous events with the CFOV plots has provided a clearer indication as to whether particular flux tubes are moving towards or away from Saturn, or not moving at all. This is significant because the ability to determine the flow direction of these flux tubes, and hence the plasma, is important in establishing plasma circulation patterns in the kronian magnetosphere and hopefully in answering the question of whether Saturn
exhibits general or isolated (as fingers or bubbles) plasma flow, or a combination of all of these.

Using the CFOV plots we determined that the events on the 28th October 2006 and some of the events on the 28th October 2004 were moving inward. This is contrary to what was reported previously by Russell et al. [2006] and Burch et al. [2007].

5.8.2 Magnetic field signatures

Our extensive survey has shown that while the latitudinal dependence of the magnetic field strength, shown by André et al. [2007], applies for the most part, it is not a strict relation. We found some exceptions, such as events with increases in magnetic field strength that were not at the equator.

It is believed that the flux tube content is probably not from picked up plasma, as the energies do not correlate with calculated pickup energies.

We were not able to investigate the hypothesized pressure balance within the system. Whilst it is straightforward to measure the magnetic pressure it is considerably harder to calculate the plasma pressure inside the flux tube. Ion moments are limited and their determination infrequent, and inside the flux tube it is not possible to use ELS moments because we cannot confidently calculate the spacecraft potential. For some events it was feasible to glean electron densities using the RPWS instrument and from these it appeared that they were in pressure balance, but there were not enough observations to be
certain of this, bearing in mind that ions dominate electrons in their contribution to the total pressure balance. As future work for this investigation it would be beneficial to use the electron densities from the RPWS instrument in order to estimate the expected spacecraft potentials, and thus improve the moments calculated by ELS.

5.8.3 Pitch angle distributions

The pitch angle distribution analysis results do mostly agree with what has been presented previously [Rymer, et al., 2008], addressing the third motive in section 5.4. One particularly interesting event was on the 19th of December 2007 as this showed mostly isotropic distributions, indicating a newly created injection event in which the pitch angles had not had time to evolve. The events on this date also did not fit the latitude-magnetic field dependence idea and these events were very young. Thus we speculate that we have found the “birth place” of a plasma bubble, observing it soon after creation, before it has had time to disperse. The difference in appearance between the flux tube ions (which are high energy only) and the usual corotating plasma could be further evidence that the flux tube population possibly originated elsewhere. This is a significant and useful result as it has not been reported on before, and the events on this date could be investigated further in order to learn more about bubbles and their transport inside the magnetosphere.

It would be beneficial for further investigation of these injection events if we could request some spacecraft time during which the CAPS instrument is
aligned to either point in the nominal corotation flow arrival direction or in the field of view of the observed velocity. This would allow the observation of the injected flux tube beam at the center of the field of view so that hopefully all the ions can be measured. This is suggested because many examples do see the corotation direction and Saturn but are lacking in data coverage in the radial direction. These two suggestions would give better coverage for the CFOV plots which would enhance and strengthen any future survey, and hopefully mean that in the future outward flowing plasma can also be unambiguously detected.
CHAPTER 6  LOW ENERGY ELECTRON ENHANCEMENTS ASSOCIATED WITH SATURN’S MOON ENCELADUS

“...You wouldn’t be trying to make yourself feel better with a round of Kick the Spike?”

Spike, BTVS, episode 5.13.

6.1 ABSTRACT

During an investigation of thermal plasma observations by CAPS, we noted short duration enhancements in the fluxes of low energy electrons immediately before, during, or after the occurrence of microsignatures and plasma cavities associated with the moon Enceladus. These features sometimes appear as single electron flux enhancements, but are often observed to appear as a set of discrete spikes, covering electron energies up to 100 eV and lasting, intermittently, up to tens of minutes. A survey of these perplexing features was carried out in order to learn more about the spikes and to attempt to discover possible causes for their occurrence. Several processes, including dust impacts and spacecraft charging were considered as potential causes, as was the possibility of plasma instabilities in Enceladus’s wake. We conclude that there are several types of spikes observed in the vicinity of Enceladus and that different types of spikes could be formed by different processes. Although we isolate several potential formation processes, we believe that none of them is responsible for all the signatures observed in this study.
Chapter 6: Spikes

6.2 Introduction

The electron enhancements investigated here were first found in the vicinity of energetic particle cavities associated with satellites, termed microsignatures. Due to their possible relevance to the spikes’ formation, we describe them in some detail here. As introduced in chapter 2, Saturn's large inner moons are continuously immersed in the planet’s radiation belts. The moons are thus exposed to the energetic particle populations surrounding the planet. Absorption of radiation belt particles occurs at the moons, creating cavities that lead and trail the moons’ motion [Roussos, 2008]. In order to fully understand the nature of the cavities created by the absorption of particles, it is first necessary to discuss the motion of these particles in the magnetosphere.

6.3 Drift motion and cavities

Cavities are caused by the absorption of particles drifting around Saturn. The longitudinal drift of charged particles begins because of the presence of the corotational electric field (and thus the “E × B” drift) and magnetic curvature and gradient drifts. If only the “E × B” drift is taken into account, both ions and electrons drift in the same sense as corotation (eastwards for Saturn, when viewed in the equatorial plane). However, gradient and curvature drifts become more important as a function of increasing energy and decreasing L shell. For ions the magnetic drift velocity is parallel to the corotational drift, but for electrons the magnetic drift velocity acts in the opposite direction to the
corotational drift. The longitudinal angular velocity of a particle in an inertial frame is described in equation 6.1.

\[ \omega = \Omega \pm \omega_D \]  

where the total azimuthal drift motion is \( \omega \), the co-rotation drift is \( \Omega \) and the magnetic drift is \( \omega_D \) [Thomsen & Van Allen, 1980]. The plus (minus) sign is used for ions (electrons).

At a particular energy, the transition energy \( E_T \), the electron magnetic drift will be equal and opposite to the electron corotation drift and \( \omega \) will equal 0. Some example transition energies are given in table 5. For high energy values (\( E >> E_T \)) the magnetic drifts thus dominate the electron motion.

<table>
<thead>
<tr>
<th>Moon</th>
<th>L shell</th>
<th>Pitch Angle</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>10°</td>
<td>60°</td>
<td>90°</td>
<td></td>
</tr>
<tr>
<td>Tethys</td>
<td>4.88</td>
<td>1.73</td>
<td>1.30</td>
<td>1.23</td>
<td></td>
</tr>
<tr>
<td>Enceladus</td>
<td>3.95</td>
<td>2.20</td>
<td>1.67</td>
<td>1.58</td>
<td></td>
</tr>
<tr>
<td>Mimas</td>
<td>3.092</td>
<td>2.93</td>
<td>2.22</td>
<td>2.10</td>
<td></td>
</tr>
</tbody>
</table>

**Table 5: Example transition energies for three of Saturn’s moons.**

From [McAndrews, 2007]

If the magnetic drift is greater than the co-rotation drift the electrons drift westward against corotation in the inertial frame (electrons are always drifting westwards in the frame rotating with Saturn). Thus \( E_T \) is important in order to define whether electrons are travelling with or against corotation. Ion magnetic drifts are in the same sense as corotation and hence there is no \( E_T \) for ions. If only the magnetic drift patterns are taken into account, ions travel around
Saturn in the same direction as the major moons’ orbital motion and electrons travel around Saturn in the opposite direction. Low energy electrons travelling in the corotation direction drift with speeds lower than the corotation speed, and high energy ions drift faster than the co-rotation speed. $E_T$ is shown in the cartoon in figure 93.

When in the frame of reference where the moon is stationary, the angular velocity ($\omega_K$) of the moon’s orbital motion must be taken into account, as described in 6.2.

$$\omega - \omega_K = \Omega \pm \omega_d - \omega_K$$

6.2

If the terms on the left hand side of equation give a positive value the angular velocity is eastward relative to the moon. If they give a negative value the motion is westward and if the terms equal zero, a resonant energy can be found, as described in equation 6.3.

$$\Omega \pm \omega_d - \omega_K = 0$$

6.3

The resonant energy, $E_R$, of the system, is defined as the energy at which the particle in question is moving at the same rate as the moon around the planet. If this is the case, the particle may never impact the moon, escaping absorption altogether.

If the fraction of corotation at a particular L shell is taken into account, equation 6.4 can be considered, where $f$ is a parameter denoting the fraction of corotation at that L shell, assuming non-rigid co-rotation and $\omega_R$ is the resonant angular velocity [Roussos, 2008].
\[ \omega_R = f \Omega \pm \omega_D - \omega_K \]

6.4

Using these equations, it can be seen that there are various different scenarios for electron motion that are energy dependent.

If the electron energy, \( E \), is less than \( E_R \), electrons are travelling in the same sense as corotation, faster than the orbital motion of the moon but slower than the corotation speed. Thus, the electrons are absorbed on the trailing face of the moon, leading to a cavity downstream of the moon, i.e. ahead of the body in its orbit about Saturn.

If \( E_R < E < E_T \), electrons drift with corotation but the moon is drifting faster than the electrons. This means that absorption occurs on the leading edge of the moon and hence the cavity is observed upstream (trailing the moon).

For higher energies, and if \( E > E_T \) electrons travel westward against the moon’s orbital motion and co-rotation, so absorption is on the leading face of the moon and cavities are seen on the upstream side of the moon.

As a rule of thumb, it can be said that low energy electrons and ions form a downstream cavity, leading the moon’s orbital motion while higher energy electrons form an upstream cavity, trailing the moon’s orbital motion. These scenarios are illustrated in figure 93.
Figure 93: a) energy-velocity plot showing how electron and ion motion is affected by the resonant and transition energies. b) cartoon depicting the motion of electrons and ions in the frame of reference moving with the moon. The flow of particles creates upstream or downstream wakes depending on the direction of flow and the particle concerned.
6.4 Particle absorption

There are various ways in which a particle can avoid absorption, some of which are shown in figure 94. If a particle with 90° pitch angle has a gyroradius smaller than the moon radius the particle will collide with the body, but if the gyroradius is larger the particle can “leapfrog” the moon. Leapfrogging occurs when longitudinal distance covered by a particle during its bounce motion is larger than the diameter of the moon added to the distance the moon moves in that time. If a particle with a pitch angle between 0° – 90° or 90° – 180° is considered, the corkscrew effect can occur. This is when the guiding centre passes through the moon without the particle itself colliding, if the gyroradius combined with the distance the particle moves along a field line is larger than the moon’s radius, and the phase of gyration is conducive to non-absorption. If any of these occur it would mean that the particle doesn’t impact the surface of the moon and hence avoids absorption [Paranicas & Cheng, 1997; Thomsen et al., 1977].
The moons’ orbital paths relative to the plasma corotation direction must be taken into account as well. Moons on elliptical orbits only travel exactly parallel with the corotating plasma at periapsis and apoapsis. This can explain why some cavities can be seen away from moons’ instantaneous distances from Saturn, especially Mimas, which has the most eccentric orbit of the large

Figure 94: cartoons describing the different methods of absorption of a particle on impacting a moon surface. (a) and (b) describe a particle with 90° pitch angle and a gyroradius of similar scale to the moon itself. In a) impact occurs whereas in b) the particle has a gyrophase conducive to passage past the moon without impact. (c) and (d) shows the corkscrew effect for particles with non-90° pitch angles, where a particle avoids absorption due to its gyrophase (c) or relatively long bounce period (d) even though its guiding centre for motion passes across the moon.

From Roussos et al. [2008]
moons. However, other processes are likely to be responsible for the large shifts in L shell that are often observed.

Absorption regions also effectively drift due to them being regions where there is an absence of particles that would have drifted had they not been absorbed by a moon i.e. the region drifts at the same rate as the particles around it. Hence, the cavities can travel in the magnetosphere in the same way as flux tubes that have not been depleted of content, effectively drifting around Saturn at the same velocity as if the particles have not been absorbed. The cavity can sometimes be observed at significant distances from a moon as the cavities refill. This means that a spacecraft can sample cavities formed in the past without having to traverse the depleted flux tube when directly connected to a moon. The cavity is observed in the data as a sharp drop in counts relative to surrounding regions: particles on neighbouring flux tubes which have not traversed the moon have not been absorbed [Van Allen et al., 1980b].

On the basis of past observations, the cavities were grouped into two categories [Paranicas & Cheng, 1997; Van Allen et al., 1980a]. The first are macrosignatures, which are azimuthally averaged and time independent. These are permanent, caused by constant absorption, for example, by ring material due to its continuous presence at a particular L range. Macrosignatures also appear in high energy ion data because those ions have large gyroradii and, if they encounter a moon frequently, which can occur at very high energies due to their rapid drift motion, are lost continually over a large radial range. The second, termed microsignatures, are transient. These are dependent in nature on the longitudinal distance between the observed signature’s location and the
absorbing body due to the energy dependence of the particle drift velocities [Jones, et al., 2006; Paranicas et al., 2005; Roussos et al., 2007].

### 6.5 Microsignatures

Both macro- and micro- signatures are seen in the data as a decrease in the count rate of the particles but, for microsignatures, the depth of the signature can indicate how long ago the signature was formed. Generally, the deeper the feature the closer to the moon the spacecraft was at the time of observation. The microsignature is not permanent; the cavity is refilled by dispersion processes and diffusion, so if the spacecraft is further from the moon in Saturn longitude, the depth of the signature decreases and the feature can be broader [McAndrews, 2007]. Microsignatures provide an excellent tool for probing a moon’s environment. Examining them can aid investigations into the diffusion processes of different particle populations, plasma processes at active bodies, the widths of the absorbing bodies, energetic electron dynamics, and other aspects of the magnetospheric environment.

An example high energy microsignature for Enceladus is shown in figure 95, in data from CAPS-ELS obtained on the 9th of March 2005. This microsignature was crossed upstream of Enceladus, and shows a drop in background, penetrating radiation. Low energy microsignatures, occurring downstream of Enceladus, only show a drop in foreground counts.
Eleven close flybys of Enceladus occurred between February 2005 and May 2010. Relevant details of the encounters can be found in table 6.
The flyby geometries, speeds and closest approach (CA) distances vary greatly over the ten flybys discussed. E2 revealed with certainty the active nature of the moon and by 2006 it became apparent that not only did the moon have active fissures, termed 'tiger stripes', in its south polar region but that these cracks in the surface were erupting plumes of icy grains, water vapour and other gases into the local environment [Dougherty, et al., 2006]. Two years passed until E3, when Cassini travelled directly through the plume, sampling the emitted materials. The flybys can be organised in a variety of different ways in order to investigate them further. Figure 96 shows all the flybys organised by the different types of encounter. There are three groups: the encounters

<table>
<thead>
<tr>
<th>Flyby</th>
<th>Date (DOY)</th>
<th>Time at CA (UT)</th>
<th>Altitude at CA (km)</th>
<th>Actuator position</th>
<th>Dust?</th>
<th>Spikes?</th>
<th>Dispersion features?</th>
</tr>
</thead>
<tbody>
<tr>
<td>E0</td>
<td>17/02/2005 (40)</td>
<td>03:30</td>
<td>1260</td>
<td>Fixed</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>E1</td>
<td>09/03/2005 (68)</td>
<td>09:08</td>
<td>497</td>
<td>Fixed</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>E2</td>
<td>14/07/2005 (195)</td>
<td>19:55</td>
<td>166</td>
<td>Fixed</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>E3</td>
<td>12/03/2008 (72)</td>
<td>19:06</td>
<td>47</td>
<td>Fixed until 19:15</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>E4</td>
<td>11/08/2008 (224)</td>
<td>21:06</td>
<td>50</td>
<td>Fixed until 21:20</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>E5</td>
<td>09/10/2008 (283)</td>
<td>19:06</td>
<td>25</td>
<td>Fixed until 19:25</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>E6</td>
<td>31/10/2008 (305)</td>
<td>17:14</td>
<td>197</td>
<td>Actuating</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>E7</td>
<td>02/11/2009 (306)</td>
<td>07:41</td>
<td>99</td>
<td>Fixed until 08:30</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>E8</td>
<td>21/11/2009 (325)</td>
<td>02:09</td>
<td>1602</td>
<td>Actuating</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>E9</td>
<td>28/04/2010 (118)</td>
<td>06:10</td>
<td>99</td>
<td>Fixed until 06:30</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>E10</td>
<td>18/05/2010 (138)</td>
<td>06:04</td>
<td>434</td>
<td>Fixed until 06:15</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 6: Table containing information about eleven enceolaidan flybys. The main text will explain the columns labelled dust, spikes and dispersion features.
upstream of the plume (E0, E1, E2, E10), the encounters which traversed the plume in a north-south direction (E3, E4, E5 and E6) and the southern encounters which crossed the plume in a direction perpendicular to the plume axis (E7, E8, E9, E11). These are discussed in more detail in the following sections.
Figure 96: plots showing the Cassini encounters with Enceladus during close flybys. The top panel of each is looking along the thermal plasma wake, with north upwards, the corotation flow coming out of the page and Saturn to the right. The bottom panel of each is looking down from the north, corotation flowing from the top to the bottom and Saturn to the right. The corotation wake is shown in green.

From [Kempf, S., J. Schmidt, et al., manuscript in preparation].
6.6.1 **Flybys upstream of Enceladus: E0, E1, E2, E10**

These flybys are shown in figure 97. The first flyby of Enceladus, E0, gives an example of a microsignature in the high energy electron wake. The higher energy electrons are severely depleted by the moon giving a microsignature which should be approximately the diameter of Enceladus.

This event is important because after the microsignature there is evidence of the spikes that are the focus of this investigation (circled in black on the figure). If viewed with the penetrating radiation removed the spectrogram uncovers something more complex than these spikes. The low energy electron features are seen to extend to energy-time dispersed signatures, shown and discussed...
in more detail in section 6.10 of this chapter. These dispersion signatures are usually indicative of injection processes. Having discovered these features during E0 the Enceladus encounter datasets were investigated in greater detail and at present, more than 20 dispersion events have been discovered in the vicinity of Enceladus L shell.

The ELS energy-time spectrogram for E2 gives an example of how the electrons are absorbed by the moon, leaving a microsignature approximately the width of the moon. Spikes are also observed on the same date as the E2 flyby, but are not shown in figure 97.

During the E10 flyby the microsignature of Enceladus has shifted in relation to where it was during E0, even though the trajectories are similar, possibly due to the effects of a possible noon-night electric field in the region [M. Andriopoulou et al., Icarus, in preparation, 2012]. Spikes are apparent again, but this time on either side of the microsignature and inside the microsignature itself (circled in black on the figure).
6.6.2 ENCOUNTERS WITH THE PLUME IN A NORTH-SOUTH DIRECTION: FLYBYS E3-E6

Figure 98: Flybys during which Cassini crosses the plume, largely in a north-south direction; E3, E4, E5 and E6. FAE denotes field aligned electrons, D denotes dust, N denotes negative ions and DR denotes a dropout due to dust. TP indicates a dropout due to the thermal plasma wake/corotation wake. Features of interest are annotated in this plot, other features also occur.

These flybys are shown in figure 98. E3 traverses the low energy plasma wake and the plume. Before CA we see the high energy penetrating radiation, this is absorbed by the moon, creating a microsignature approximately the width of
the moon. Negative ions (N on the E3 plot) are observed [Coates et al., 2010a] as well as negatively charged dust (D on the E3 plot) after CA [Jones, et al., 2006]. E5 is very similar to E3 except that at CA it reaches just 25 km from the surface of Enceladus whereas CA for E3 is 47 km. Flybys E4-E6 have steeply inclined trajectories with respect to Enceladus (more so than E3), meaning Cassini spends longer in the wake for these flybys. This can be seen in figure 96. During E5 there is a magnetic field aligned feature in anode 3, going up to about 1 keV (FAE on the E5 plot), as can be seen in the E5 plot in figure 98 at 19:03 UT. It is possible that this is the signature of a connection between Enceladus and Saturn's ionosphere [Pryor et al., 2011]. We do not address these features in this thesis.

E3 and E5 both show signs of a low energy electron dropout at CA (DR on the E3 plot), which may be due to electrons being absorbed by dust in the surrounding environment [Farrell et al., 2009; Farrell et al., 2010].

E4 shows a field aligned electron enhancement just before CA and signs of a 'double' microsignature. There are field aligned electrons (FAEs, FAE on the E4 plot) present which may again be part of the population forming an auroral footprint of Enceladus at Saturn. The E6 flyby, like E4 and E5, also had a largely north-south orientation although there is a large component of the motion from downstream to upstream. Again there is evidence of FAE beams for the fifteen minutes before CA (FAE on the E6 plot) and negative ions are apparent.
6.6.3 **Flybys perpendicular to and through the plume; E7, E8, E9 and E11**

During these flybys Cassini has different trajectories but, for each one, passes through the plume with a small velocity component in the north-south direction remaining near the southern surface of the moon during each encounter. However, each flyby has a different distance to Enceladus at CA. These flybys are shown in figure 99.

![Figure 99: Plume-traversing flybys perpendicular to the plume axis; E7, E8, E9 and E11. FAE denotes field aligned electrons, DR denotes a dropout. Features in E11 are circled in black. Only features of interest are annotated in this plot.](image-url)
During E7 the ELS was operated at a lower operating level to avoid damage to the instrument, as it was expected that Cassini would be passing through a dense part of the plume. Use of this instrument mode led to a noisier dataset. There are electron enhancements after CA (FAE on the E7 plot), up to about 10 eV, but possibly also the same low energy electron dropout due to dust as noted for E3 and E5 (DR on the E7 plot).

E8 has enhancements before and after CA, reaching 30 eV, and the instrument is actuating throughout the flyby. The electron dropout is present at CA, but shifted in relation to where it was seen at E7.

During the E9 flyby the electron dropout is seen just after CA (DR on the E9 plot), at 00:10 UT. The electron enhancements occur after the microsignature and reaches energies of over 10 eV.

During the E11 microsignature there is an enhancement in electrons, circled in black. These are probably electrons from the plume and are isotropic, so are less likely to be negative ions.

The detailed analysis of Enceladian flybys shows that spikes can happen upstream and downstream of the moon, and at different locations in relation to the microsignatures. Spikes are described in greater depth in the next section.

6.7 “Spikes”

As mentioned, during the investigation of close flybys and microsignatures of Enceladus, discrete, short duration electron flux enhancements generally at
energies lower than 100 eV, which we term “spikes”, were found in the low energy electron plasma. They are often observed in close proximity to the moon's L shell, at varying latitudes and energies. On some occasions the spikes are clearly associated with dispersion signatures. The observation of these dispersed spikes indicates that some of the spikes are older features when observed, i.e. they can persist long enough for dispersion to occur. Such signatures have not been previously documented so close to Saturn. These spikes have been seen close to the L shell of Enceladus, with observations in Cassini data from 2005 until the middle of 2010, i.e. from southern summer to post-equinox, so at present their occurrence does not appear to be seasonal. Analysis of the pitch angle distributions reveals that there is no obvious additional enhancement of electron flux parallel to the magnetic field direction, indicating that the electrons responsible for the spikes are not necessarily field aligned electrons. However in some cases, at the spike observation time, there is a coincident fluctuation in the magnetic field direction and magnitude which could signify that the spikes are associated with ULF waves in the kronian magnetosphere [Leisner et al., in preparation].

Spikes were observed initially in data from moon flybys and associated observations of microsignatures. The presence of spikes has been noted in eight of the flyby encounters described in section 6.6. Of these flybys, three are coincident with the observation of charged dust during the plume encounter.
6.7.1 **SPIKE OBSERVATIONS**

6.7.1.1 **CASE STUDY: 30TH MARCH 2005**

![Time-energy spectrogram of ELS data showing spikes around 01:45-01:50 UT.](image)

*Figure 100: Spikes observed on 30th March 2005, between 01:45 and 01:50 UT. The spikes reach energies up to 100 eV.*

Figure 100 is a time-energy spectrogram of ELS data, showing an example of spikes between 1:45UT and 1:50UT. The spacecraft was near the equator at this time at a Saturn local time (SLT) of 22:08 LT when the spikes began to occur. When the spectrogram, within which penetrating radiation has been removed, is plotted against L shell rather than against time, figure 101, spikes are observed between L = 3.835 and 3.85, and can be resolved into smaller features, covering an L shell range of 0.015 Rs in total, approximately 900 km.
The electron flux enhancements were at low energies, only reaching up to 100 eV.

![Energy-L shell spectrogram showing spikes from the 30th March 2005.](image1)

**Figure 101:** Energy-L shell spectrogram showing spikes from the 30th March 2005.

The radial scales of the spikes can be estimated using this type of plot.

For this case study there was no microsignature present. This could be for a number of reasons, for example, the geometry could be inappropriate for searching for the microsignature or the low energy microsignature could be sensitive to spacecraft orientation. Figure 102 shows energy spectra at discrete times, referred to as timeslices through the spectrogram in figure 100, for anode 5 during a time when a spike is and isn’t present. It can be seen that during the spike there is an increase in the count rate between 8 and 50 eV.

During the spikes the pitch angle distribution appears to become slightly more field aligned than before or after the spikes (when they seem to be isotropic), but the pitch angle coverage is not sufficient to be confident of this.
From this case study we can see that these particular spikes are limited to low energies, with a radial width about double the diameter of Enceladus in total. They were observed in the nightside of Saturn and are approximately equatorial.

**Figure 102:** Timeslices through the energy-time spectrogram for the 30th March 2005. The left hand plot is before the spikes, the right hand plot is during the spikes. The dashed line shows the level that would be registered by one electron in each energy bin.
6.7.1.2 **Case study: 17th February 2005**

Figure 103 demonstrates another example of spikes in the Enceladus L shell region. The top plot is an energy-time spectrogram from CAPS-ELS for the 17th February 2005, the E0 flyby. The bottom plot shows DEF for several energy channels.

The spikes appear during the period from 3:30 UT to 3:36 UT and are preceded by a microsignature of the moon ending at 3:29 UT. The spike energies are low, between 10 and 30 eV. There was no obvious enhancement parallel to the
magnetic field direction signifying that the electrons responsible for the spikes are not necessarily field aligned electrons. However, the pitch angle coverage is only 40° wide (from 90° to 130°) so it is hard to draw meaningful conclusions from the data. The spikes are also often too discrete to be able to confidently measure the pitch angles during the spikes. The radial width of the microsignature is measured to be approximately $0.01R_S$, about 600 km, which is expected as this is the approximately the diameter of Enceladus (Enceladus's diameter = 502 km). As a group the spikes are observed with scales up to $0.01 R_S$. These particular spikes appear after the microsignature, but others have been observed before, after and during microsignatures, irrespective of whether Cassini was travelling towards or away from Saturn, and when microsignatures are not observed at all in the ELS data. When the penetrating radiation background is subtracted from the data it becomes apparent that these particular spikes are not finite structures, but parts of dispersion signatures covering much larger energy and time ranges (shown later in figure 109). During this time the pitch angle distribution shows that the electrons are mostly isotropic, without great indication of 90° or field aligned electrons during the spike. At $L = 4.5$ the equatorial loss cone has a size of approximately 4.4° which is relatively small. There is no significant change in the magnetometer data during this period nor any indication of alterations in the phase space density between when the spikes are occurring and when they are not. The dispersion features are described in greater detail in later sections.


6.8 **SPIKE DETECTION**

6.8.1 **AUTOMATED SPIKE FINDER**

On closer inspection of the data, it was clear that hundreds of such events were present near the Enceladus L-shell. An algorithm was developed to objectively and automatically search for spikes in ELS data spanning over five years. Spikes were found by first subtracting smoothed data from the original data. The smoothing was done using the IDL ‘smooth’ function, which employs a boxcar filter to smooth data. For the search, electron flux data were smoothed using user defined average box/filter width. The filter width was investigated and it was found that a width of 15 was used for this investigation. This indicates that in the smoothed data set each point is the average of a 15 data point set from the original data array. The smoothed flux data were then subtracted from the original data, and any discrete, brief enhancements in flux, with a flux differential greater than 1000 relative to the background flux, that then became apparent, were checked and catalogued. This process is shown in figure 104.

![Figure 104: Cartoon showing the smoothing process that was used in the automated spike finder. The blue line is the real data for one spike. The red line is the smoothed data for the same spike. If the flux differential is 1000 or greater, this data is counted as a spike.](image-url)
Candidate events were then inspected by eye to remove false positives. Although the algorithm employed produced an objective set of candidate events, all sampling biases could not be removed completely. These included changes in instrument temporal and energy resolution, pitch angle coverage, occasional data outages, and perhaps most significantly, the background level in ELS data caused by instrument-penetrating energetic particles. Such penetrating radiation is able to completely obscure any electron features in the data, meaning that some spikes may be hidden and never observed.

The spike occurrence rate was normalised with respect to time spent at each L shell and latitude to attempt to remove sampling biases caused by variable coverage resulting from Cassini’s complex orbital tour. Guided by the energies of previously identified spikes, the primary run investigated spikes between 9 and 15eV. The automated program detected numerous injection events which were separated from the actual spikes for further investigation.

6.8.2 Manual Detection

For a more thorough analysis, manual spike detection (and sometimes elimination) complemented the automated search program. In the Enceladus L shell region, which was defined for the purposes of this study as being between L = 3.5 and 4.5, the L shell-time spectrograms were studied visually and any spikes observed were noted. ELS spectrograms plotted against time do not easily or accurately convey these features’ radial length scales. Plotting L shell-time spectrograms instead enhanced our spike survey; many spikes that were previously seen to be brief in time were now seen to be reasonably extended in
radial distance, and vice-versa, depending on Cassini’s motion at the time of observation. To find these electron enhancements by eye, inbound and outbound data were studied from SOI to June 2010 when the spacecraft’s periapsis was smaller than L=4.5. For the dates when these criteria were met, spikes of the dispersive nature as described in figure 103 were flagged and their details were recorded. The Enceladus close flybys were investigated in greater detail for any similar electron enhancements. Data from the CAPS Ion Mass Spectrometer (IMS) were searched for corresponding ion enhancements, but no clear coincident features were found, reasons for which will be discussed in section 6.11.3. Using this manual process a plethora of spikes between L = 3.5 and 4.5 were found, and the results of the survey follow in section 6.9.

6.9 Results of the survey

Searching for spikes in the ELS data was challenging. There are high levels of penetrating background radiation which could conceal features and influence results (background radiation can be seen in the spectrogram in chapter 3, figure 39). Spikes also had appearances that differed depending on the instrument temporal and energy resolutions at the time of detection.
The histogram in figure 105 describes the results of the preliminary run, between $L = 3$ and 8.5, from SOI until June 2010, normalised for the amount of time Cassini spent at each location. It can be seen that there are many spikes detected by the code. It is possible to see that more spikes are observed outwards of Enceladus's L shell at $L = 3.95$. There is a clear peak near the orbit of Tethys, but investigating the cause of this peak was deemed to be outside the scope of this thesis. It could be possible that the decrease of spike occurrence inwards of the orbit of Tethys may be due to the increase in penetrating radiation masking faint spikes in the ELS data.
In total, over 600 spikes were found between $L = 3.5$ and 4.5 from data between SOI and June 2010, as shown in the normalised histogram in figure 106.

The spikes appear in different forms; some are wide and diffuse, while others resolve into clusters of discrete spikes. Spikes are generally restricted to lower energies, under 100eV. Their energy range and length scales do not seem to be functions of L shell or of distance from the moon. Spikes tend to be quite narrow; most are no wider than $\sim 600$km. While these features were first noticed due to their close vicinity to enceladian microsignatures they are also quite common away from the L shell. However the fact that spikes cluster around microsignatures means that both might be linked.

Figure 106: Normalised histogram showing frequency of spikes found as a function of L shell within the chosen region.
Spikes seem to be more prevalent outside Enceladus's L shell, and in longitude tend to be more common near the position of Enceladus. However there are varying sample sizes in longitude difference-L shell space which may impact the results.

Figure 107: Cassini's trajectory plotted as L shell against longitude difference near Enceladus's orbit (solid horizontal line). Superimposed on the path are the locations of observed signatures. Red diamonds denote microsignatures, circles are spikes found manually, triangles are spikes found by the automated program, squares are spikes during close flybys. The solid blue circle denotes the location of Enceladus.

Figure 107 shows a longitude difference-L shell frequency plot of all spikes within the Enceladus region, extended all the way around Enceladus's orbit, with Cassini's trajectory over plotted as a solid line. The longitude difference
gives the angular separation between the spike and the moon, and the sign of this separation describes whether the spike was found upstream (positive longitude difference) or downstream of the moon (negative longitude difference). Spikes seem to be more prevalent outside Enceladus's L shell, and in longitude tend to be more common near that of Enceladus. However the results are affected by varying sample sizes in longitude difference-L shell space. Whilst most spikes are clearly found outside Enceladus's L shell there is no strong pattern for spikes occurring up- or downstream. The automated program detected a few spikes that were not obvious to the naked eye. Spikes that are specifically associated with the close flybys have a tendency to be downstream and outside of the moon’s L shell. Most spikes are found just north of the equator with a peak at between 0° and 4°. The magnetic equator is displaced north of the rotational equator by 0.037 Rs (approximately 2230 km) [Dougherty, et al., 2005], so perhaps this indicates a concentration of spikes at the magnetic equator, which is possible as at Enceladus, the latitude of the magnetic equator can be calculated to be approximately 0.53°. A histogram showing the latitudes of the spikes, normalised for the amount of time Cassini spent at those latitudes, is shown in figure 108.
Figure 108: Normalised histogram showing frequency of spikes found as a function of latitude within the chosen region.
6.10 Dispersion Features

With the penetrating background radiation removed, it became apparent that the spikes observed during the first Enceladian flyby, E0, were coincident with, and possibly directly related to, dispersion signatures.

![Cassini data 2005:048 (17-feb) Actuator range: FULL](image)

**Figure 109**: E0 spectrogram with penetrating radiation removed, enhancing the dispersion features suspected of being associated with the spikes.

Figure 109 shows how these low energy electron features appear to extend to dispersive higher energy signatures. Dispersion features are generally associated with injection events, e.g. [Hill, et al., 2005], as discussed in chapter 5. The association between these dispersion features and the spikes discovered
within this study, e.g. during E0, gives possible evidence of small-scale injection processes occurring in the inner magnetosphere.

During a more in-depth investigation of the region between L=3.5 and L=4.5, we found twenty other dispersion features. The ages of these features were estimated using an equation from [Hill, et al., 2005] (as discussed in chapter 5), taking into account the co-rotating plasma and the orbital motion of Enceladus. Ages varied between hours and tens of hours, but the majority were found to be 10 to 20 hours old. From the knowledge of the signature’s ages and their separation from the moon, their source location with respect to the moon at the time of formation could be estimated. The dispersion features’ observed positions and inferred source locations could provide evidence that the features are created near Enceladus but this is not the only option. No obvious pattern in the inferred source positions was found, but the majority of dispersion feature ages tend to be less than 18 hours, which is the time it takes for a packet of thermal plasma to re-encounter Enceladus in its orbit. Figure 110 shows an L shell-longitude plot depicting the dispersive spikes’ observed locations and equivalent source locations. Whilst most features are found outside Enceladus’s L shell, there does not appear to be any other discernible pattern in the results.
Figure 110: L shell-longitude difference plots for the observed positions and equivalent inferred source locations for the spikes that were observed to extend into dispersion signatures. Errors were first calculated for the age of the spike and then converted into an error in longitude for the inferred source locations.
6.11 A DISCUSSION OF CANDIDATE FORMATION PROCESSES

Several candidate processes by which these features could be formed are considered and examined in this section.

Spikes have varying characteristics; some are dispersed, sometimes the energy differs (non dispersing spikes are generally seen between 10 and 100 eV), some are single flux enhancements whereas others are discrete clusters of spikes. This is suggestive of several formation mechanisms operating; different processes may explain the variation in characteristics.

6.11.1 SPACECRAFT CHARGING

We investigated the possibility of spacecraft charging being a cause of the spikes [Khurana et al., 1987]. Rapid changes in spacecraft potential could conceivably occur as a result of the change in incident energetic particle fluxes when the spacecraft crosses microsignatures. Such effects can be ruled out as the cause of these spikes primarily because the spikes occur both before and after microsignatures, so it’s not believed to be a change in energetic particle flux causing them.
Plots of phase space density (PSD) against energy were created for times before, during and after the spikes. A simulated dataset was created using a spacecraft potential of varying amounts to alter the phase space density of the pre-spike electron population, as if spacecraft charging was occurring. This simulated dataset was then compared to the real data. It can be seen in figure 111 that the simulated dataset does not match the actual data. A potential of -5 V was assumed in this case. For a ‘real’ spike or for the background electron population, the phase space density decreases smoothly. For the simulated data of a spike due to spacecraft charging there is an increase in phase space density under 10eV. This hump becomes more pronounced as the spacecraft potential increases.

Figure 111: A plot of phase space density against energy for the 30th March 2005 event. The solid line is during the spike, the dotted line is before the spike. The dashed line is the simulated data if the spike were created due to spacecraft charging.
The analysis was repeated for various spacecraft negative potential levels and in each case no match was found for the behaviour observed in the real data. This indicates that the spikes are not due to spacecraft charging.

6.11.2 **Thruster firings**

The possibility that the spikes were created due to the firing of thrusters on the spacecraft was also investigated. Such firings could conceivably temporarily increase the local plasma density enough to be detected by ELS. The dates and times of the spikes were compared to thruster firing dates and times [M. Burton, private communication] and it was found that none of the times matched, indicating that the firings of the thrusters do not contribute to spike formation. Close inspection of the data around the firings revealed no discernible signatures; an example of a period during which thrusters were fired is shown in figure 112. However, it may be useful in the future to compare thruster firing times with inferred source locations rather than observed locations of spikes.
6.11.3 Moon Surface Charging

The surface of Enceladus is expected to be electrically charged; the surface charging of icy moons has been addressed by Roussos et al. [2010]. The moon’s surface is expected to possess a negative potential due to the high plasma density in its vicinity.

The magnitude of the negative potential depends greatly on the illumination of the surface by sunlight. The potential can reach up to a negative few kV for extreme cases at the larger moons but are more typically in the range of 0 to -100 V [Roussos, et al., 2010] although these values are not specifically for
Enceladus. Electrons flowing along magnetic field lines that intersect the moon's surface encounter this negative potential and are reflected if their energy in eV is lower than the magnitude of potential measured in Volts, and then can be detected by the spacecraft when in a suitable location. The electron beam would therefore have a maximum energy corresponding to the moon's surface potential. Secondary electrons that are liberated at the surface can also be accelerated by the electric field near the moon's surface. Surface charging has been observed at another kronian moon, Rhea, as shown in figure 113.

When traversing above the surface of Rhea, low to medium energy spikes were observed to be coming from the surface, due to the charging of the moon. These spikes bear similarity to the spikes seen at Enceladus, but the charging process could be more complex than at other moons due to the presence of charged dust in the enceladian plume. Dust can affect the equilibrium of the charged particles because if the dust becomes charged it will have an electric potential, and tends to have a negative potential due to the fact that electrons are more mobile than ions [Melzer & Goree, 2008].

It has been speculated that the spikes at Rhea may result from gradients in surface potential in the vicinity of the terminator on the moon's surface. The solar zenith angle, SZA, is that between the local zenith and the line of sight from that point to the Sun. Rhea has been modelled to possess a positive potential of approximately 1 V at SZA lower than 30° but by a SZA of 90° the potential reaches up to -70 V [Roussos, et al., 2010].
Perhaps low energy electron enhancements discussed here are formed by the same process as the Rhea spikes, but due to the plume having a charge in addition to the surface of the moon. In such a scenario, electrons travel along the magnetic field lines, towards the plume. Negatively charged plume grains give the plume a net negative potential. When the travelling electrons meet this potential they are reflected back along the field line and are detected by CAPS, and because of the net negative potential the spikes are only seen in the electron data not the ion data. The low energy spikes that are seen upstream

Figure 113: An plot against time of DEF over a full range pitch angles for electrons of energies between 824 eV and 2112 eV, during a Rhea close encounter on the 2nd March 2010. There is a clear microsignature during which the electron flux drops, creating a "bite out" that is approximately the width of the moon. This plot shows the spikes are arriving at pitch angles \( \geq \sim 120^\circ \), which is in the direction of the moon.
during flybys could be created there, or at Enceladus and survive an entire drift period around the planet. From the same process, spikes could be caused by the surface charging of Enceladus, giving rise to spikes downstream. From the geometry of the encounters it is possible to determine whether the electrons would be reflected from the charged moon or the charged plume. In order to test this hypothesis it could be possible to check dust location in relation to spike location by using the Cassini Cosmic Dust Analyser (CDA) group's dust jet simulations [Kempf, 2008] and by investigating the pitch angle distribution of these features; the pitch angles can indicate whether the electrons are travelling directly from the plume or dusty areas. However, the potential levels indicated by the spikes do seem higher than the levels expected; Enceladus’s plume is expected to charge negatively only to about -2 V [J. Saur, private communication] whereas the spikes can reach up to 100 eV, i.e. indicating a potential of -100 V. Figure 114 shows a pitch angle distribution plot for the E10 flyby. The plot indicates that spikes are coming from >100° pitch angle, which for the spacecraft’s location is the direction of the plume. These spikes are arriving only from one general direction. However, other spikes observed are more isotropic. It is possible that the spikes are created due to plume or moon charging, hence are field aligned, but become more isotropic with age, perhaps due to counterstreaming populations.
6.11.4 Injection events

Spikes may have also been seen in relation to injection events. DeJong et al. [2010] report an increase in low energy electron flux, between 12 and 100 eV, during injection events. We investigated whether these phenomena are related. Some of the electron spikes at Enceladus are energy-dispersed; something to our knowledge that has not been previously noted. Any spike will eventually be dispersed if it covers a wide energy range. Whilst a dispersed signature isn’t always indicative of an injection event this could be a possible cause, linking...
the possible mechanism processes for spikes to those processes discussed in chapter 5.

Injection events travelling inwards from \(L = 13\) to the \(L\) shell of Enceladus could be the most plausible explanation for energy dispersed signatures across the \(L\) shell and longitude range observed in this study. The spikes could be injected flux tubes, as discussed in chapter 5, which have travelled in towards Saturn. The reason that they look different to the injection events surveyed in the previous chapter is because they are closer to the planet and have travelled further. This idea can be supported by the fact that the ages of the injection events in this study are older than the injection events in the study in chapter 5, thus have had more time to travel and are found at a smaller \(L\).

Another possible, but perhaps less likely, mechanism for this process is believed to be that the moon itself, and the plume, absorb a portion of the local plasma population. This removal of part of the plasma population may lead to small-scale injection events; i.e. the moon itself or the presence of its wake may be responsible for the formation of these injection features. If plasma has been removed, other material may move in to fill the evacuated region (although this does not necessarily mean the plasma swaps place with other plasma, in which case it would be an interchanging feature). Either the dispersion features are created at the moon or the plasma instability causes a flux tube to move inwards in order to refill the absorbed material. If the features are small-scale injections this can be proven by checking for pitch angle distributions and compressions or depressions in the magnetic field magnitude (as discussed in chapter 5). The spikes that have been investigated in this way have not so far demonstrated any coincident fluctuations in the magnetic field data nor a
specific pitch angle distribution, but this may be something that becomes more apparent in the future with a larger dataset. One limitation of looking for these dispersion events at L=4 is that identification becomes challenging due to high energetic electron background levels close to Saturn.

### 6.11.5 Electrodynamic Interactions

Some of the spikes could be ‘fossil’ signatures of the moon-planet electrodynamic interaction.

This hypothesis is based upon the observation that some auroral beam electron features are seen to extend up to high energies, more than 3 keV, but a lower-energy population is observed as well. Electrons seem to “flicker” between the low energy and high energy states and it is possible that the low energy population might be a better match to the spikes while the higher energy population are evidence of the auroral footprint. The flickering between energies is not yet well understood but is believed to be linked to magnetic field perturbations, as an equatorial signature of a standing wave pattern.

Electron beams are seen during the E4 and E6 flybys; these are field aligned beams detected by the ELS instrument [Pryor, et al., 2011]. This electrodynamic interaction is known to accelerate electrons but when the source of these features disappears, the accelerated electrons should continue to drift near Enceladus’s L shell where they can remain observable for several hours or more. It could be these populations of electrons that are sometimes being observed as spikes, particularly if these are observed at off equator
latitudes as opposed to isotropic distributions which are observed near the equator.

It is also possible to consider pseudo-auroral processes occurring due to the exosphere of Enceladus. Enceladus is an unmagnetised body, however a pile up of magnetic field lines exists at the south pole due to the plume, which could be the cause of a weakly induced magnetosphere. The plume creates a localised exosphere, electrons travel down magnetic field lines and meet this, electron impact ionization occurs and electrons are emitted, which perhaps are observed as spikes [Khurana, et al., 2007; Ledvina et al., 2004; Luhmann et al., 2004]. Electron impact ionization in the Enceladus exosphere/neutral cloud area is thought to require energies of a few eV, and produce electrons escaping with isotropic pitch angles [Burger et al., 2007; Johnson et al., 2006]. Thus, low energy electrons could cause ionization as well as charging the dust in the vicinity. These parameters fit well with our observations of spikes.

**6.12 Conclusions and future work**

Low energy electron enhancements, termed spikes, were first serendipitously observed, then sought out in the ELS data from Saturn Orbit Insertion in July 2004, until mid 2010. Spikes were detected primarily between \( L = 3 \) and \( L = 8.5 \) within the kronian magnetosphere even though the search was across the entire magnetosphere. It was decided that the Enceladus region between \( L = 3.5 \) and \( 4.5 \) should be our focus of attention due to the fact that many spikes
were observed during close flybys of the moon, suggesting a possible link between moons and these puzzling electron features.

Over 600 spikes were found in the Enceladus region; the majority are below 100 eV in energy and narrow in radial dimension, with many not exceeding 600 km, and some as narrow as approximately 200 km. The spikes did not appear to have a pattern in location in terms of longitude difference from Enceladus and most were found about the equator, which seems to link directly to the location of the magnetic equator. Inspection of pitch angle distributions revealed that most of the spikes were isotropic, but some associated with flybys were found to be field aligned.

On closer inspection it was observed that some of the spikes could be resolved into dispersion features. These features were analysed and their ages were estimated to determine where they originated, but no obvious pattern in their source locations was observed.

The spikes appear to be linked to Enceladus, due to their proximity to the moon’s orbit, and although at present no concrete cause has been established for their occurrence, it is clear that they are worthy of more detailed analysis. The spikes do not appear to reach much higher energies so it is unlikely to be beneficial to look at the Magnetospheric Imaging Instrument data for their signatures, which observes charged particles of >20 keV. However, a multi-instrument study of these spikes may give a greater understanding of them in the future; particularly once new enceladian flyby data are available.

Close flybys of the moon Enceladus have shown previously that negative ions, photoelectrons and charged dust exist around the L shell of the moon, due to
the interaction between its plume and the surrounding environment [Coates et al., 2010b; Dougherty, et al., 2006; Farrell, et al., 2010; Jones et al., 2009].

It is believed that there are many types of spikes observed in the Enceladus region and hence observed spikes could be formed by several different processes. The spikes can be classified into at least three subsets: a general picture including isotropic signatures with elevated fluxes up to a few tens of eV, spikes with a clear dispersion signature at higher energies and field aligned spikes. Using this classification it would be useful to know if each of these different types had different distributions in L, local time, latitude and whether they are associated with an upstream or downstream microsignature.

It was possible to rule out spacecraft charging and thruster firing during the analysis but several other candidate processes remain under consideration.

The surface charging of the moon and/or the plume with a negative potential could cause electrons to be reflected back from the moon along the magnetic field line to be detected by the instrument as spikes. These types of spikes are likely to be the most common in occurrence and of the lowest energies (under 100 eV). It would be useful as future work to set up a collaboration with the Cosmic Dust Analyser group in order to use their dust simulations to investigate if dust locations correlate with spike locations. This would show whether some spikes are due to high density regions of the plume containing negatively charged dust reflecting electrons.

Spikes that can be resolved into dispersion features could be injection events travelling inwards from L = 13 to the L shell of Enceladus or could be caused by small scale injection events, in which the absorption of the local plasma
population by the moon induces an injection of plasma to refill the evacuated wake. Only 20 were observed during this survey, but it is possible that more exist. However, it is difficult to observe these dispersed spikes because often the dispersion signature is obscured by penetrating radiation in the region. A larger dataset of dispersed spikes would allow for more age calculations and hence the opportunity to investigate more fully the source locations of these spikes. With a larger dataset it might be possible to see a pattern in the spike source location. It would also be useful to study more of these dispersed spikes in terms of local time and source location, as with a larger dataset it could be possible that this type of spike tends to be created in a particular local time.

The moon could become charged in different ways at different local times [Roussos, et al., 2010], which could lead to spikes being created at one particle local time/sector.

The spikes seen to extend to higher energies could be signatures of moon-planet electrodynamic interactions, such as the auroral footprint of Enceladus to Saturn and related fossil signatures.

Looking at the total population of spikes rather than only those near the Enceladus L shell, the majority were seen between $L = 3$ and $L = 8.5$, with a peak at Tethys’s L shell. There may be spikes inside of $L=3$ but it is difficult to observe them due to the penetrating radiation in that area. The cause of the peak at Tethys is of interest but was outside the scope of this thesis, and would be prime material for future work.
CHAPTER 7  SUMMARY AND FUTURE WORK

“Even I was bored. And I’m a science nerd.”

Willow, BTVS, episode 1.12

In this thesis plasma and magnetic field data from the Cassini spacecraft was used, covering the period from Saturn orbit insertion on the 1st July 2004 to the 17th June 2011, in order to investigate the influences, interactions and dynamics of Saturn's magnetosphere. Supporting data from some other instruments onboard the spacecraft were also analyzed in order to better understand the dynamics of Saturn's magnetosphere, the influences on it, and interactions with the bodies contained within it. Three separate topics were investigated, but they are linked as all concern the magnetosphere and the dynamics of the plasma therein.

7.1 SATURN’S MAGNETOPAUSE

The first topic, presented in chapter 4, considered the size and shape of Saturn’s magnetopause by establishing a new model for it. The new model is the focus of a published paper [Kanani, et al., 2010], and has been used in a number of further studies and has been referenced therein, for example [Bagenal & Delamere, 2011; Provan et al., 2012; Pryor, et al., 2011; Snowden et al., 2011]. The new pressure balance model was developed using multi-instrument data analysis, building on past models and includes new features. It
has been shown that the model has improved on previous models due to the inclusion of a variable solar wind thermal pressure in the pressure balance equation, and use of directly measured total magnetospheric plasma pressure, providing more accurate results. The results support findings from previous models in that the magnetopause size scales differently to that expected of a dipole with a fixed magnetic moment.

The new model gives a magnetopause which is slightly larger than previous model magnetopauses due to the introduction of additional parameters in the fitting technique, such as the hot plasma pressures, leading to a higher estimated dynamic pressure at the boundary. The new model magnetopause is more streamlined than previous models because of the inclusion of a dynamic pressure-dependent thermal static pressure.

It has been shown that this model has improved on previous models due to the inclusion of the suprathermal plasma and variable static pressures in the pressure balance equation, resulting in more realistic results. Thus, we suggest that it is the most accurate representation of Saturn’s magnetopause to date.

The model could be expanded in a number of ways. Firstly, the inclusion of new crossings, since the last iteration of the model was carried out, should be included. This would include any crossings between 2006 and 2012.

It would be beneficial to include effects relating to periodic motion of the magnetopause [Clarke, et al., 2006] and a larger dataset would allow the investigation of polar flattening, high latitude effects and seasonal effects.
Our model used estimated solar wind speed but for a more accurate representation of Saturn’s magnetopause, actual values of the solar wind speed would ideally be used. However this is not possible with a single spacecraft, thus the most appropriate tool available is the Michigan Solar Wind Model (mSWiM) (http://mswim.engin.umich.edu/). This model can estimate solar wind conditions beyond the orbit of the Earth. The mSWiM uses in situ solar wind measurements made near Earth and other inner heliosphere locations and propagates these conditions to outer Solar System objects, such as Saturn, using a 1D MHD model. The inclusion of this model into a new magnetopause model would make such a magnetopause model more accurate.

Other issues with the new model include the fact that, as yet, it has been assumed that the magnetopause is in equilibrium and is axisymmetric. Assuming a pressure balance also assumes that the magnetopause is static but in reality this is by no means necessarily the case. In order to ensure correct pressures have been accounted for it is imperative to have inbound and outbound crossings.

7.2 Injection events and plasma dynamics

The second study, chapter 5, investigated flux tube interchange and injection events in Saturn’s inner magnetosphere. A new survey of these features was carried out from Saturn Orbit Insertion until the 17th of June 2011 in order to test previous models of Saturn’s magnetospheric conditions.
The survey concentrated on large scale, young injection events in the inner magnetosphere, in the CAPS-ELS energy range with coincident increases or decreases in the magnetic field strength. A total of 60 injection events on 38 separate dates were observed.

The initial aim was to determine the flow direction of the interchanging flux tubes, and if this was possible then it would be possible to infer a minimum velocity of the travelling flux tube. Injection events with increases or decreases in magnetic field strength were of particular interest because they had been classified as both inward and outward flowing in separate past studies, and latitude dependent; we wanted to test these hypotheses.

We presented case studies of several events observed by the CAPS instrument. By re-examining the electron and ion data we were able to make conclusions based on results from the survey.

A new method was created to estimate the radial plasma flow direction of interchanging flux tubes. Pitch angle distributions, magnetic field data and plasma flow models were also considered in order to help establish plasma circulation patterns in the kronian magnetosphere.

The majority of injection events with increases in magnetic field strength were found about the equator, with the majority of events with decreases in magnetic field strength away from the equator, in broad agreement with the hypothesis of latitude dependence by André et al., [2007]. Injections were primarily observed around local midnight and local noon and ages varied between a tens of minutes and a few hours. Outward flowing flux tubes were not confidently observed. Injection events whose flow directions were
determined were used in order to infer the velocity of the flux tube, with speeds in the region of 100 – 200 km/s. Using these speeds it was possible to infer source locations; there appeared to be a group between L = 6 and 18 and another between L = 22 and 28.

The ability to determine the flow direction of the plasma associated with injection events aided the investigation of plasma circulation patterns, and from the results of the survey we were able to hypothesize that in the kronian magnetosphere it is highly likely that general and isolated (bubbles) plasma flow exists.

Pitch angle distribution analysis was thought to demonstrate one particularly interesting event which had isotropic pitch angles before, during and after the injection event. From these results we speculate that we have found the “birth place” of a plasma bubble. This is a significant and useful result that has not been reported on before and the events on this date could be investigated further in order to learn more about these bubbles and their transport inside the magnetosphere.

A prime focus for future work would be to further investigate these injection events as more data become available, particularly if we were able to request some spacecraft time during which the CAPS instrument is pointing in the nominal corotation flow arrival direction or in the direction of the injection flux tube beam at the center of the field of view. This would give better coverage for the CFOV plots which would enhance and strengthen any future survey, and hopefully mean that in the future outward flow direction of plasma can also be unambiguously determined.
7.3 LOW ENERGY ELECTRON ENHANCEMENTS

The third topic, presented in chapter 6, concerns low energy electron enhancements associated with Saturn’s moon Enceladus.

Low energy electron enhancements, termed spikes, were first serendipitously observed, then sought out in the ELS data from Saturn Orbit Insertion in July 2004 until mid-2010. Spikes were detected primarily between $L = 3$ and $L = 8.5$ within the kronian magnetosphere even though the search was across the entire magnetosphere. The Enceladus region, between $L = 3.5$ and $4.5$, was the focus of attention due to the fact that many spikes were observed during close flybys of the moon.

Over 600 spikes were found in the Enceladus region; the majority are below 100 eV in energy and narrow in radial dimension, with many not exceeding 600 km. The spikes did not appear to be clustered in any particular longitudinal separation from Enceladus, but in latitude most were found about the equator. Inspection of pitch angle distributions revealed that most of the spikes were isotropic, but some associated with flybys were found to be field-aligned. On closer inspection it was observed that some of the spikes could be resolved into dispersion features. These features were analysed and their ages were estimated, but no obvious pattern in their source locations was observed.

The spikes appear to be linked to Enceladus and although at present no concrete cause has been established for their occurrence, it is clear that they are worthy of more detailed analysis.
It is believed that there are many types of spikes observed in the Enceladus region and hence observed spikes could be formed by several different processes. It was possible to rule out spacecraft charging and thruster firing during the analysis but several other candidate processes remain under consideration.

The surface charging of the moon and/or the plume with a negative potential could cause electrons to be reflected back from the moon along the magnetic field line to be detected by the instrument as spikes. These types of spikes are likely to be the most common in occurrence and of the lowest energies (under 100 eV). It would be useful as future work to set up a collaboration with the Cosmic Dust Analyser group in order to use their dust simulations to investigate if dust locations correlate with spike locations. This could show whether some spikes are due to high density regions of the plume containing negatively charged dust reflecting electrons.

Spikes that can be resolved into dispersion features could be injection events travelling inwards from L = 13 to the L shell of Enceladus or could be caused by small scale injection events, in which the absorption of the local plasma population by the moon induces an injection of plasma to refill the evacuated wake. Only 20 were observed during this survey, but it is possible that more exist. However, it is difficult to observe these dispersed spikes because often the dispersion signature is obscured by penetrating radiation in the region. A larger dataset of dispersed spikes would allow for more age calculations and hence the opportunity to investigate more fully the source locations of these spikes. With a larger dataset it might be possible to see a pattern in the spike
source location. It would also be useful to study more of these dispersed spikes in terms of local time and source location, as with a larger dataset it could be possible that this type of spike tends to be created in a particular local time. Some of the spikes could be signatures of moon-planet electrodynamic interactions, such as the auroral footprint of Enceladus to Saturn and related fossil signatures although some of the electrodynamic interaction electrons are also at lower energies [Pryor, et al., 2011].

The majority of spikes were seen between $L = 3$ and $L = 8.5$, with a peak at Tethys’s $L$ shell. There may be spikes inside of $L=3$ but it is difficult to observe them due to the penetrating radiation in that area. The cause of the peak at Tethys is of interest but was outside the scope of this thesis, and would be prime material for future work.

### 7.4 Thesis summary

These topics, along with associated future work on each, are lengthy and complicated subjects in their own right. The first provides the size and shape of an important boundary to the magnetosphere hence is useful in investigating the magnetosphere as a whole, the second gives a diagnostic for plasma transport within the magnetosphere which is important for the dynamics of the system and the third provides an insight into the sources and sinks of plasma in the magnetosphere and processes therein, describing more about Saturn-moon interactions and influences on the magnetosphere.
An exciting amount of information could yet be discovered about the kronian system. If Cassini continues operating in orbit around Saturn until 2017, as is currently planned, it could provide us with a plethora of new information, delving deeper into the kronian system and enabling scientists to answer many of the remaining unanswered question.
APPENDIX A

COORDINATE SYSTEMS AT SATURN

There are many different coordinate systems in the study of Saturn’s magnetosphere, and this section highlights the ones used in this thesis.

In general terms, the following letters are used for the following coordinates:

X: a unit vector in the x-axis

Y: a unit vector in the y-axis

Z: a unit vector in the z-axis

K: a unit vector in the rotation axis

S: a unit vector from Saturn to the Sun

M: a unit vector in the direction of the magnetic dipole

The Cartesian system has X pointing along the Saturn-Sun line, Z pointing along the planet’s spin (and magnetic) axis while the X-Z plane contains the Sun and Y completes the set. Sometimes it is more convenient to use the cylindrical ρ-Z system in which ρ is the perpendicular distance from the axis of symmetry and Z is the distance along the axis from the equatorial plane.

The Spacecraft system is fixed relative to Cassini. –X is along the MIMI CHEMS field of view (but by no means based around the CHEMS instrument), –Y is along the field of view of the optical remote sensing instruments, and –Z is along the look direction of the high gain antenna.
The Kronocentric Solar Magnetospheric (KSM) system is analogous to the GSM system for Earth. It is a magnetospheric system but because the magnetic field and rotation axis at Saturn are so closely aligned, the use of the terms rotation axis and magnetic dipole axis are interchangeable. $X$ is equivalent to $S$ and points from Saturn to the Sun. $Y = \frac{K \times X}{|K \times X|}$ and is perpendicular to the rotation axis, towards dusk. $Z = X \times Y$ is chosen so the rotation axis lies in the X-Z plane.

The KRTN system is the radial-tangential-normal system in which $R$ is the radial component, $T$ is the tangential component and $N$ is the normal component. This coordinate system is based on the location of the spacecraft relative to the Sun and the Sun's rotation axis. It is a spacecraft centered coordinate system.

The KRTP system is the Kronographic body fixed spherical system in which $R$ is the radial component, $T$ is the southward component and $P$ is the eastward component. The $R$ axis is radially outward from Saturn, the $P$ axis is in the direction of the cross product of Saturn's rotation axis and the $R$ axis, and the $T$ axis completes the right-hand coordinate system.

These coordinate systems are shown in figure 115.
Figure 115: Cartoons showing some of the coordinate systems used within this thesis. From [Arridge, et al., 2012].
Table 7. This table summarises the main characteristics of the injection events used in this survey. Part 1.

<table>
<thead>
<tr>
<th>Date</th>
<th>Time (UT)</th>
<th>L shell</th>
<th>Latitude (°)</th>
<th>Local Time</th>
<th>Magnetic Field Strength Fluctuation Direction</th>
<th>Calculated Age (hours)</th>
<th>Minimum Inferred Velocity (km/s)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>10th Jan 2011</td>
<td>20:34</td>
<td>4.7</td>
<td>0.1</td>
<td>10:19</td>
<td>Increase</td>
<td>0.469</td>
<td>272</td>
<td>one of them is inwards</td>
</tr>
<tr>
<td>10th May 2011</td>
<td>18:25</td>
<td>6</td>
<td>-0.2</td>
<td>02:55</td>
<td>Increase</td>
<td>0.92</td>
<td>-</td>
<td>seem stationary but too narrow to be sure</td>
</tr>
<tr>
<td>10th May 2011</td>
<td>19:50</td>
<td>6</td>
<td>-0.3</td>
<td>03:05</td>
<td>Increase</td>
<td>0.72</td>
<td>-</td>
<td>seem stationary but too narrow to be sure</td>
</tr>
<tr>
<td>11th Jul 2009</td>
<td>02:20</td>
<td>5.8</td>
<td>-2.8</td>
<td>09:40</td>
<td>Increase</td>
<td>2.42</td>
<td>-</td>
<td>seem stationary but too narrow to be sure</td>
</tr>
<tr>
<td>11th Jul 2009</td>
<td>02:25</td>
<td>5.9</td>
<td>-2.4</td>
<td>09:42</td>
<td>Increase</td>
<td>3.47</td>
<td>-</td>
<td>seem stationary but too narrow to be sure</td>
</tr>
<tr>
<td>12th Oct 2006</td>
<td>04:32</td>
<td>6.3</td>
<td>1.5</td>
<td>14:21</td>
<td>Increase</td>
<td>1.46</td>
<td>-</td>
<td>seem stationary but too narrow to be sure</td>
</tr>
<tr>
<td>13th Feb 2010</td>
<td>22:10</td>
<td>4.9</td>
<td>-0.3</td>
<td>12:37</td>
<td>Increase</td>
<td>3.75</td>
<td>86</td>
<td>beam gets narrower so must be inwards</td>
</tr>
<tr>
<td>13th Oct 2009</td>
<td>19:10</td>
<td>7.5</td>
<td>-0.2</td>
<td>00:25</td>
<td>Increase</td>
<td>1.47</td>
<td>215</td>
<td>appears to be inwards</td>
</tr>
<tr>
<td>16th Jan 2006</td>
<td>21:20</td>
<td>7.8</td>
<td>-0.3</td>
<td>12:19</td>
<td>Increase</td>
<td>1.27</td>
<td>-</td>
<td>appear to be stationary</td>
</tr>
<tr>
<td>17th April 2011</td>
<td>06:10</td>
<td>5.2</td>
<td>-0.2</td>
<td>02:53</td>
<td>Increase</td>
<td>0.42</td>
<td>-</td>
<td>beam gets narrower but doesn’t seem to move: stationary</td>
</tr>
<tr>
<td>17th April 2011</td>
<td>07:10</td>
<td>5</td>
<td>-0.3</td>
<td>03:32</td>
<td>Increase</td>
<td>0.44</td>
<td>-</td>
<td>beam gets narrower but doesn’t seem to move: stationary</td>
</tr>
<tr>
<td>17th Nov 2007</td>
<td>01:10</td>
<td>6</td>
<td>2.7</td>
<td>20:50</td>
<td>Increase</td>
<td>2.2</td>
<td>-</td>
<td>not actuating so can’t tell</td>
</tr>
<tr>
<td>17th Nov 2007</td>
<td>02:15</td>
<td>5.5</td>
<td>2.8</td>
<td>21:30</td>
<td>Increase</td>
<td>2.4</td>
<td>75</td>
<td>beam gets narrower so must be inwards</td>
</tr>
<tr>
<td>20th Jul 2007</td>
<td>19:06</td>
<td>5.4</td>
<td>-0.2</td>
<td>02:21</td>
<td>Increase</td>
<td>2.12</td>
<td>-</td>
<td>looks like it could be out but its very short so hard to tell</td>
</tr>
</tbody>
</table>
Table 8: This table summarises the main characteristic of the injection events used in this survey. Part 2.

<table>
<thead>
<tr>
<th>Date</th>
<th>Time (UT)</th>
<th>L shell</th>
<th>Latitude (°)</th>
<th>Local Time</th>
<th>Magnetic Field Strength Fluctuation Direction</th>
<th>Calculated Age (hours)</th>
<th>Minimum Inferred Velocity (km/s)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>21st Jul 2007</td>
<td>07:00</td>
<td>8</td>
<td>-0.3</td>
<td>08:08</td>
<td>Increase</td>
<td>1.9</td>
<td>46</td>
<td>can't see a beam so must be inwards</td>
</tr>
<tr>
<td>21st March 2006</td>
<td>04:30</td>
<td>7.2</td>
<td>0.2</td>
<td>18:57</td>
<td>Increase</td>
<td>0.153</td>
<td>-</td>
<td>coverage isn't very good but possibly inwards</td>
</tr>
<tr>
<td>21st March 2006</td>
<td>04:50</td>
<td>7.4</td>
<td>0.3</td>
<td>19:03</td>
<td>Increase</td>
<td>0.149</td>
<td>-</td>
<td>coverage isn't very good but possibly inwards</td>
</tr>
<tr>
<td>21st March 2006</td>
<td>05:20</td>
<td>7.5</td>
<td>0.3</td>
<td>19:17</td>
<td>Increase</td>
<td>0.145</td>
<td>-</td>
<td>coverage isn't very good but possibly inwards</td>
</tr>
<tr>
<td>21st March 2006</td>
<td>07:40</td>
<td>8.5</td>
<td>0.3</td>
<td>19:56</td>
<td>Increase</td>
<td>0.259</td>
<td>90</td>
<td>most probably inwards</td>
</tr>
<tr>
<td>21st Nov 2009</td>
<td>12:50</td>
<td>6.2</td>
<td>0.2</td>
<td>13:30</td>
<td>Increase</td>
<td>1.78</td>
<td>-</td>
<td>stationary</td>
</tr>
<tr>
<td>24th Apr 2007</td>
<td>13:20</td>
<td>6.7</td>
<td>2.4</td>
<td>01:32</td>
<td>Increase</td>
<td>1.36</td>
<td>-</td>
<td>seems stationary</td>
</tr>
<tr>
<td>24th Dec 2005</td>
<td>16:10</td>
<td>5.9</td>
<td>-0.2</td>
<td>14:29</td>
<td>Increase</td>
<td>1.97</td>
<td>153</td>
<td>seems inwards</td>
</tr>
<tr>
<td>24th Dec 2005</td>
<td>16:29</td>
<td>5.5</td>
<td>-0.2</td>
<td>14:39</td>
<td>Increase</td>
<td>4.01</td>
<td>-</td>
<td>too narrow to be sure</td>
</tr>
<tr>
<td>27th Nov 2005</td>
<td>15:23</td>
<td>5.2</td>
<td>0.4</td>
<td>21:02</td>
<td>Increase</td>
<td>2.123</td>
<td>-</td>
<td>too narrow to be sure</td>
</tr>
<tr>
<td>27th Nov 2005</td>
<td>19:23</td>
<td>6.7</td>
<td>0.4</td>
<td>22:56</td>
<td>Increase</td>
<td>1.235</td>
<td>-</td>
<td>too narrow to be sure</td>
</tr>
<tr>
<td>28th Apr 2010</td>
<td>04:00</td>
<td>5.6</td>
<td>0.1</td>
<td>11:53</td>
<td>Increase</td>
<td>0.985</td>
<td>-</td>
<td>too narrow to be sure</td>
</tr>
</tbody>
</table>
Table 9: This table summarises the main characteristics of the injection events used in this survey, Part 3.

<table>
<thead>
<tr>
<th>Date</th>
<th>Time (UT)</th>
<th>L shell</th>
<th>Latitude (°)</th>
<th>Local Time</th>
<th>Magnetic Field Strength Fluctuation Direction</th>
<th>Calculated Age (hours)</th>
<th>Minimum Inferred Velocity (km/s)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>28th Oct 2004</td>
<td>19:30</td>
<td>7.9</td>
<td>0.6</td>
<td>22:30</td>
<td>Increase</td>
<td>0.559</td>
<td>-</td>
<td>too narrow to be sure</td>
</tr>
<tr>
<td>28th Oct 2004</td>
<td>19:40</td>
<td>8.4</td>
<td>0.4</td>
<td>22:33</td>
<td>Increase</td>
<td>0.552</td>
<td>214</td>
<td>seems inward because can't see the beam</td>
</tr>
<tr>
<td>30th Oct 2005</td>
<td>07:40</td>
<td>7.0</td>
<td>0.4</td>
<td>23:13</td>
<td>Increase</td>
<td>0.31</td>
<td>117</td>
<td>seems inward because can't see the beam</td>
</tr>
<tr>
<td>7th April 2010</td>
<td>05:40</td>
<td>-6.2</td>
<td>-6.1</td>
<td>00:59</td>
<td>Increase</td>
<td>4.82</td>
<td>103</td>
<td>seems inwards</td>
</tr>
<tr>
<td>19th Dec 2007</td>
<td>20:20</td>
<td>10.9</td>
<td>-11.9</td>
<td>09:44</td>
<td>Increase</td>
<td>0.13</td>
<td>110</td>
<td>must be inward because beam disappears but also see field aligned features</td>
</tr>
<tr>
<td>19th Dec 2007</td>
<td>20:41</td>
<td>10.9</td>
<td>-11.1</td>
<td>09:48</td>
<td>Increase</td>
<td>0.52</td>
<td>132</td>
<td>must be inward because beam disappears but also see field aligned features</td>
</tr>
<tr>
<td>19th Dec 2007</td>
<td>21:15</td>
<td>10.9</td>
<td>-10.7</td>
<td>09:53</td>
<td>Increase</td>
<td>0.1</td>
<td>120</td>
<td>must be inward because beam disappears but also see field aligned features</td>
</tr>
<tr>
<td>19th Dec 2007</td>
<td>22:00</td>
<td>10.9</td>
<td>-10.4</td>
<td>09:58</td>
<td>Increase</td>
<td>0.25</td>
<td>131</td>
<td>must be inward because beam disappears but also see field aligned features</td>
</tr>
<tr>
<td>28th Oct 2006</td>
<td>03:45</td>
<td>5.2</td>
<td>5.8</td>
<td>14:22</td>
<td>Increase</td>
<td>1.4</td>
<td>-</td>
<td>seems stationary</td>
</tr>
<tr>
<td>28th Oct 2004</td>
<td>07:50</td>
<td>6.7</td>
<td>13.4</td>
<td>17:22</td>
<td>Decrease</td>
<td>4.39</td>
<td>-</td>
<td>too narrow to tell a direction</td>
</tr>
<tr>
<td>28th Oct 2004</td>
<td>08:10</td>
<td>6.7</td>
<td>13.5</td>
<td>17:32</td>
<td>Decrease</td>
<td>3.42</td>
<td>-</td>
<td>seems outward but hard to tell due to data gaps etc</td>
</tr>
<tr>
<td>25th Sept 2006</td>
<td>17:50</td>
<td>21:36</td>
<td>-30.1</td>
<td>10:33</td>
<td>Decrease</td>
<td>1.87</td>
<td>-</td>
<td>unusual event as even normal corotation is not as expected</td>
</tr>
<tr>
<td>25th Sept 2006</td>
<td>18:20</td>
<td>5.5</td>
<td>-33.3</td>
<td>11:02</td>
<td>Decrease</td>
<td>3.01</td>
<td>-</td>
<td>unusual event as even normal corotation is not as expected</td>
</tr>
<tr>
<td>5th Sept 2005</td>
<td>01:50</td>
<td>8.2</td>
<td>-15.8</td>
<td>11:30</td>
<td>Decrease</td>
<td>2.1</td>
<td>138</td>
<td>looks inward because can't see a beam</td>
</tr>
</tbody>
</table>
Table 10: This table summarises the main characteristic of the injection events used in this survey. Part 4.

<table>
<thead>
<tr>
<th>Date</th>
<th>Time (UT)</th>
<th>L shell</th>
<th>Latitude (°)</th>
<th>Local Time</th>
<th>Magnetic Field Strength Fluctuation Direction</th>
<th>Calculated Age (hours)</th>
<th>Minimum Inferred Velocity (km/s)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>27th Aug 2009</td>
<td>04:10</td>
<td>6.1</td>
<td>-11.5</td>
<td>02:25</td>
<td>Decrease</td>
<td>2.171</td>
<td>78</td>
<td>looks inward as can't see the beam, but during event see interesting field aligned features</td>
</tr>
<tr>
<td>27th Aug 2009</td>
<td>04:30</td>
<td>6</td>
<td>-11.6</td>
<td>02:34</td>
<td>Decrease</td>
<td>0.736</td>
<td>-</td>
<td>looks stationary but the other two near it aren't</td>
</tr>
<tr>
<td>27th Aug 2009</td>
<td>04:50</td>
<td>5.9</td>
<td>-11.8</td>
<td>02:41</td>
<td>Decrease</td>
<td>0.374</td>
<td>82</td>
<td>looks inward as can't see the beam, but during event see interesting field aligned features</td>
</tr>
<tr>
<td>11th Jul 2009</td>
<td>01:50</td>
<td>5.7</td>
<td>-6.3</td>
<td>09:28</td>
<td>Decrease</td>
<td>2.421</td>
<td>-</td>
<td>looks stationary but events are a bit too short to be sure</td>
</tr>
<tr>
<td>24th Apr 2007</td>
<td>13:00</td>
<td>6.8</td>
<td>3.9</td>
<td>01:27</td>
<td>Decrease</td>
<td>1.62</td>
<td>-</td>
<td>looks stationary</td>
</tr>
<tr>
<td>3rd Jan 2008</td>
<td>20:22</td>
<td>4.9</td>
<td>11.4</td>
<td>22:22</td>
<td>Decrease</td>
<td>2.16</td>
<td>-</td>
<td>looks stationary but it's quite a short event</td>
</tr>
<tr>
<td>28th Oct 2006</td>
<td>04:00</td>
<td>5.2</td>
<td>6.7</td>
<td>14:30</td>
<td>Decrease</td>
<td>2.69</td>
<td>-</td>
<td>first event too narrow to tell, second event appears stationary</td>
</tr>
<tr>
<td>14th Apr 2005</td>
<td>15:00</td>
<td>6.8</td>
<td>-7.5</td>
<td>12:00</td>
<td>Decrease</td>
<td>2.89</td>
<td>-</td>
<td>can't use it because CAPS isn't actuating</td>
</tr>
</tbody>
</table>


**REFERENCES**


Crary, F. J., et al. (2005). Solar wind dynamic pressure and electric field as the main factors controlling Saturn’s aurorae.


I’d like to start by, in a seemingly conceited but less self-aggrandising way than it might come across, thanking myself for this thesis. It’s been a while since I’ve accomplished something that I’m really proud of and, while it’s hard to ever be completely proud of a PhD thesis, I’m pleased that for once I actually did the hard slog to finish this tome. Thank you to me for finally putting the work in on something! And thank you to my examiners for putting up with said tome.

Thanks have to go to Ted, Robin, Lily, Marshall and, of course, Barney for keeping me company through out those long, otherwise potentially lonely nights of writing and typing. You guys have been “legen-dary”.

Thank you to everyone at MSSL who I had the pleasure of crossing paths with. The lovely ladies in the office and the canteen, Sam for sending regular job adverts, Craig as the president of HHSC, the rest of the HHSC committee, those in the swimming club, those in the social club, those who helped out during ‘my’ open day and anyone else who supported my outreach gigs, those in the football club, those in the cake club and those of you who were part of everything else. MSSL was a beautiful place to complete my PhD at and I’ll always remember it fondly.

To my housemates when I lived in Cranleigh: Walshy for the whiskey, chillies and curry nights and Jo for the wine, Galaxy bars and Desperate Housewives.

To the MSSL girls: Katherine for being my football buddy (I’ll never learn to header the ball), Alison for the careers advice, girly nights and road trips to the lab, and of course to my twin sister (from another mother) Kimboid. Kim, you gave me giggles and hugs, chocolate and Crabbies, nights out in Guildford and nights in with the dog. I couldn’t have finished the thesis without you and you helped with that process even over the internet after you left the lab. Looking forward to you being a bridesmaid at my wedding, and looking forward to being a bridesmaid at yours!

To my planetary family: Andrew C, the granddaddy of the group, Aunty Lin, cousin Annie, cheeky little cousin “HC” Johnson. Cousin Nev for being the ultimate running buddy and confidante, for our precious times up the hill chatting about long distance relationships, TV shows and new music. To the extended family of the CAPS team across the globe.

Those in ‘my’ office, 210. Cool uncle Gethla for being my bezzie during my time at the lab, for keeping it real, keeping me sane, giving me advice, jokes like Jack Dee and standup comedy material. For the snow globes and the cycling, the Apprentice and being brown, MSF and dating advice, the cups of tea that were stirred three times to the left and twice to the right, for being on the spectrum. The lab was a joy when you were there to gossip with me about vodka and Sunny D. You believed in me the whole way through, thank you.

Older brother “Captain Physics” Chris for those one-on-ones over breakfast and younger brother “is it because I is black” Yuds for all those Youtube vids.

Finally in the planetary family, I express my extreme gratitude to my supervisors and planetary biological-Dad and step-Dad, Geraint and Andrew F. Andrew F you always told it like you saw it, which helped make me become a stronger research scientist and person. Geraint, you have been the loveliest supervisor a girl could ever want. Thank you for everything, from the wide eyed bushy tailed start of my time, to the bitter drawn out end! For the advice, the laughs, the chapter iterations, the support through thick and thin, the
honesty, the cocktails on conferences, the hug when I told you I was engaged. I hope I pop your supervisor cherry well enough that you always remember me and I hope I make you proud enough to remember me fondly!

To those outside the lab: my best friend Helen C for dinners at your house in Tooting, brunches on a Sunday, staying over after a night out and keeping me sane during the tough times by letting me write you long emails. The other girls from WHS, like Cat and Zoë, for music gigs and dinner dates and sleepovers and cocktails. Helen G (and therefore James) for your advice on how to write a thesis in Word and how to slog on when you’re past your due date. To my UoM physics group where it all started. To my SSUK mentor buddies, and the students, who reminded me why I still love space. To all my friends who I’ve had to neglect during the process, but who kept me well fed and watered regardless (Rajiv and co. do you want to go for another dhosa? Well, I gotta eat even though I’m writing up! And eat I sure did).

To all my family, close and extended, near and far, those who are with us and those who no longer are.

In particular to my immediate family.

To Nikki, Chris, Ashton and Naia for reminding me that I was more than a just a PhD student (a sister and a masi first and foremost), for keeping me grounded (“We’re proper doctors, not you!” 😊) and for always believing in me, with this and with everything else I’ve done. Nik, you are my best friend and so much more than my sister. I would be a completely different person if I hadn’t had you in my life and I can’t thank you enough for everything you’ve done for me.

To my fiancé Jaz. For proposing in such a timely fashion that I had to contend with organising a wedding and writing a thesis at the same time 😊 For the emails and internet chats, the long telephone conversations, (putting up with) the tears and the tantrums, the pep talks and the confidence building, the patience and the positivity, for Skyping me until I fell asleep. For those long train journeys up and down the country during which I did a fair amount of thesis writing and for being so understanding (“You’re nearly there! Keep plodding on!”). For being my rock, my better half, my soulmate. I can’t wait to finish this so that we can finally be together as husband and wife!

To my mum and dad, Keerti and Jagdish. I don’t know where to begin with the thank yous! For letting me live back at home for most of the PhD, for feeding me, taking me on holidays and supporting me financially and emotionally. For getting Kala Bandar and King Diddly so I had someone to brush (and hence chill out with) when I was working from home. For everything in my life. For my life! For your patience and your electricity, your unconditional love and faith in me. For leaving me alone on my bad days, for chatting to me on my lonely days, for keeping me grounded and reminding me what’s really important, for never questioning, always believing and never expecting anything in return. You are my inspiration and my role models. You have given me so much over the past 30 years (I wish I could give you just a small piece in return!) and I thank you for everything from the bottom of my heart.

And finally, to Samson and Tibbs. You gave me joy and love for 18 years. A shoulder to cry on, a face to stroke, fur to snuggle in to. You were confidants, playmates and the little brothers I never had. To Samson for teaching me to wear my heart on my sleeve, and showing me your unconditional love and trust in everybody. And to Tibbs for teaching me that no matter what the past may have held, you can pick yourself up, dust yourself off and learn to love and trust again.