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The Large-Scale Structure of the Saturnian Magnetosphere

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of Philosophy*

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Declarations

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Abstract

The Cassini mission offered a unique opportunity to study the global characteristics of Saturn and its magnetosphere due to its significant spatial and temporal coverage. The mission that spanned almost half a Saturnian year covered elements of both seasons and two solar cycles. Now it is complete we can better understand how the magnetosphere of Saturn evolves over time and can identify what the key drivers are that shape its large-scale structure.

A global stress state of the Saturnian magnetosphere is determined to identify when the system is compressed, expanded, or near its ground state. The magnetic field is found to exhibit an underlying local time asymmetry, where the field is more compressed at dusk and expanded at dawn. The system remains close to its ground state throughout the Cassini era, but examples of significant perturbations to the system are identified, revealing a highly variable global structure.

The thickness of the magnetodisc current sheet that is populated by plasma sourced from the moon Enceladus is determined using fast, steep crossings of the current layer. A local time and radial structure are found that reflect the different particle motions and field responses due to magnetopause confinement. These results are essential for developing models of the Saturnian system and highlight the importance of incorporating local time variability when analysing data.

The lack of an observed cushion region in the outer magnetosphere of Saturn has been a mystery since this region exists at Jupiter and the two share similar features. Using the entire Cassini orbital dataset, we find that this phenomenon does occur but that it is rare, finding only a handful of examples. The evidence of a cushion forming at dusk at Saturn rather than dawn, as it is at Jupiter, reveals significant differences in configuration and dynamics between these two systems.

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Chapter 1

Introduction

1.1 Overview

The research in this thesis studies the large-scale structure of the low-density magnetised space environment of charged particles that surrounds Saturn, known as its magnetosphere. This system is shaped not only by the interaction between the internally generated planetary magnetic field and the solar wind, but also by currents that flow within it. Our focus will be on the equatorial current sheet populated by Enceladus-sourced plasma associated with the radially stretched magnetodisc configuration of the Saturnian magnetosphere.

To analyse spacecraft data and research the magnetosphere of Saturn requires an understanding of the fundamental physical processes that control the system. Chapter 1 will discuss the physics that underlie the formation and dynamics of a planetary magnetosphere. This content provides the foundation not only for the work presented here but for space plasma physics research in general. To begin, the context for plasma physics discussion will be Earth-based due to the wealth of knowledge and data associated with the terrestrial system. Discussions of the Saturn system will develop from these foundations in Chapter 2 where the current under-

standing of its large-scale structure will be discussed. Chapter 3 will introduce the Cassini-Huygens mission, instrumentation and data that will be used in this thesis. Chapters 4 and 5 will focus on the geometry of magnetodisc current sheet, whilst Chapter 6 will explore when this structure breaks down. Finally, Chapter 7 will give an overview of the main results from this thesis along with suggestions for future work.

1.2 A Brief History of Space Plasma Physics

The Earth's magnetic field and the aurora have been observed for thousands of years, but only in recent history has their relation been understood. In around 2000 B.C. sightings of the aurora were documented in Chinese literature and Babylonian texts in the form of scripture on baked clay tablets, ranging from 650 B.C. to A.D. 75, revealing detailed accounts of auroral morphology [Stephenson et al., 2004]. However, the cause of the aurora was unknown and explanations were often spiritual due to their mysterious quality. In addition, one of the earliest known forms of a compass for navigation was by the Chinese in the 11th century, who used lodestone to magnetise needles to point south [Cheng-Yih, 2008].

Fast forward to the 19th century and Kristian Birkeland provided a scientific explanation for the aurora. He did so by tying the phenomena to the magnetic field of Earth. Building a terrella, a magnetised sphere representing Earth invented by William Gilbert, and placing it inside a vacuum chamber, he fired a beam of electrons at the sphere, revealing a circular ring of light around the poles of the terrella (see Figure 1.2). He suggested that the driving mechanism for the aurora borealis is similar. What the electron beam resembles, the solar wind, was first coined by Eugene Parker in the 1950s [Parker, 1958a]. However, this suggestion was fiercely rejected at the time and even when accepted for publication it was met with a hostile response [Obridko and Vaisberg, 2017]. In 1957, Sputnik 1 signified the

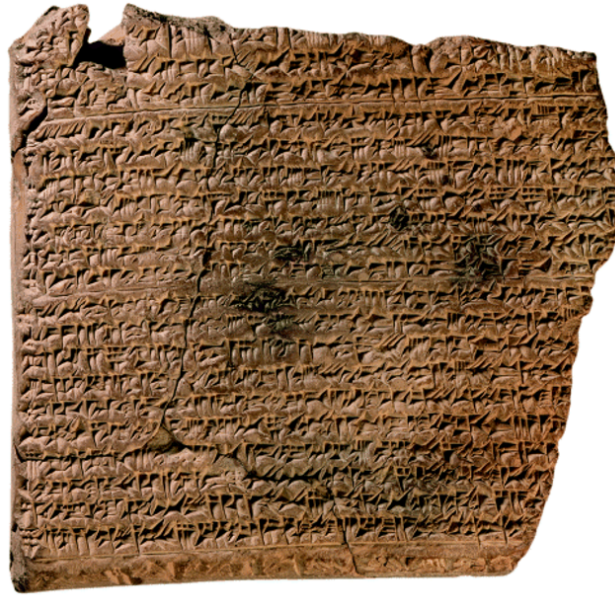


Figure 1.1: Babylonian baked clay tablet from 567 B.C. showing recordings of auroral sightings. Image from Stephenson et al. [2004].

beginning of the space age by being the first spacecraft to orbit the Earth. Not long after, in 1961, the first measurements of the boundary between the Earth's magnetic field and the solar wind, the magnetopause, were made by Explorer 12 [Cahill and Amazeen, 1963]. This description of the Sun-Earth interaction now underpins our current understanding of magnetospheric formation.

Only thirty-two years passed between the first spacecraft orbiting Earth and every planet in our solar system being visited by a spacecraft. The majority of spacecraft during this period have flown with a magnetometer, showing the significance of these measurements for space exploration. Saturn, the sixth planet from the Sun and second largest in the solar system, has now been visited by four spacecraft but has many remaining mysteries. This thesis will utilise data from the Cassini-Huygens mission, the most recent spacecraft to visit Saturn, to study the magnetic environment

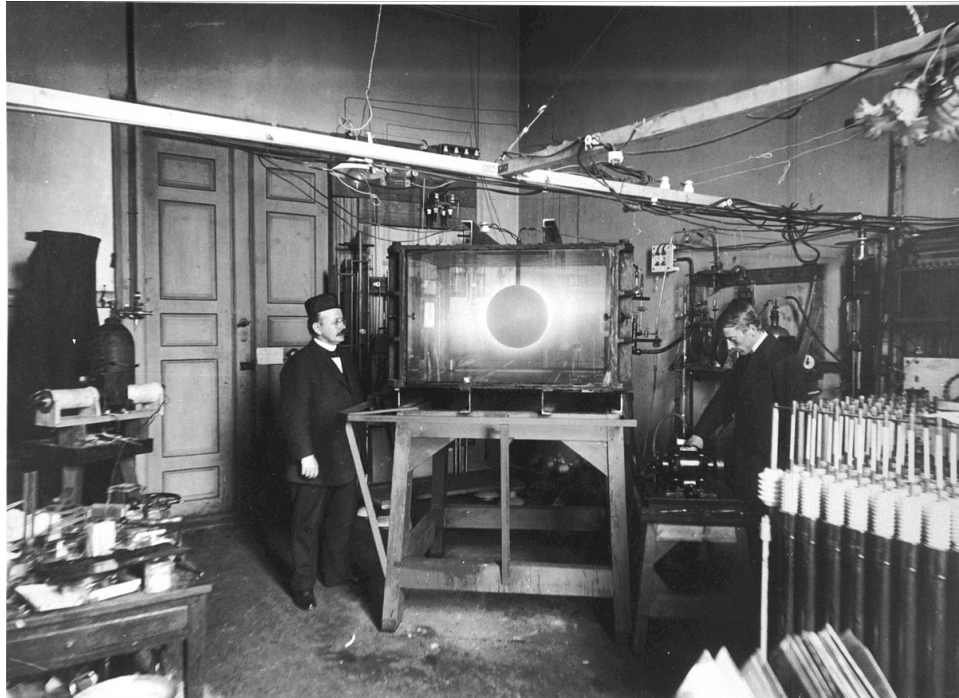


Figure 1.2: Photograph of Kristian Birkeland and Olaf Devik with a Terella in a vacuum. Image source: The Norsk Teknisk Museum.

surrounding Saturn.

1.3 What is Plasma?

The concepts discussed in the remainder of this chapter will mainly rely on content from the classic space physics textbooks of Treumann and Baumjohann [2001] and Kivelson and Russell [1995], and the lecture notes of Voss [1991], unless otherwise stated.

A plasma is often described as a quasi-neutral gas of charged particles. However there are three explicit criteria that need to be fulfilled for an ionised gas to behave like a plasma. These are:

1. **Plasma neutrality:** A plasma is a gas populated mainly by charged

particles, containing both positively charged ions and negatively charged electrons. However, on large scales it must have net-zero charge. If, for instance, an ion is introduced to a plasma, the plasma particles redistribute themselves to shield the charge of the ion. The more mobile, lower mass electrons move via the Coulomb interaction towards the ion and whilst its electric potential will still be observed close to the particle, at large distances neutrality will be restored due to the shielding by surrounding particles. The Debye length λ_D is the distance at which the ion affects its surroundings, but at scales larger than λ_D the plasma remains neutral. Collective shielding ensures *quasi-neutrality* of the plasma. Knowledge of λ_D is essential, for instance, when determining where to place instrumentation on a spacecraft to ensure the external plasma environment is measured.

2. **Plasma scale:** There must be a high enough number of electrons to ensure collective shielding can occur. This is expressed by there being far more than one electron within a sphere of radius λ_D .
3. **Plasma frequency:** Plasmas need not only contain charged particles but can be populated by neutral particles. However, collisions between neutrals and charge particles must be low, otherwise they would obstruct collective behaviour. As electrons move to ensure quasi-neutrality, they will oscillate about their new position. The frequency of this oscillation must be greater than the frequency of collisions with neutrals to ensure the behaviour of the gas is controlled by the charged particles.

1.4 Maxwell's Equations

The motion of charged particles in a plasma is determined by their interaction with electric and magnetic fields. There is an interplay between the

fields and particles associated with a plasma, whereby magnetic and electric fields affect the motion of particles and particle motion contributes to the magnetic and electric fields. This was discovered in the 18th and 19th century by a collection of scientists, who separately discovered experimentally the connection between charged particles and the electromagnetic field. These were later brought together and summarised as Maxwell's Equations, the 'axioms' of electromagnetism that are a set of four equations expressing this fascinating relationship, given here in differential form. The first of these equations is Gauss's law, given by

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0}, \quad (1.1)$$

where $\mathbf{E}$ is the electric field, $\rho = \sum_s q_s n_s$ is the charge density summed over the different species, q_s is the species charge, n_s is the species density, and ϵ_0 is the permittivity of free space $\sim 8.9 \times 10^{-12}$ F/m. Intuitively, Gauss's law describes how all charges have an associated electric field directed inwards (outwards) if it is negatively (positively) charged. Gauss's law for magnetostatics is given by

$$\nabla \cdot \mathbf{B} = 0, \quad (1.2)$$

where $\mathbf{B}$ is the magnetic field. This shows that there is zero net flux of a magnetic field through a closed surface, indicating that there are no magnetic monopoles, unlike electric fields that are associated with a single point charge. Now, foregoing the static picture presented above, the interaction between electric and magnetic fields can be understood. Faraday's law, given by

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \quad (1.3)$$

expresses that a time varying magnetic field induces an electric field. Finally, there is Ampère's law, given by

$$\nabla \times \mathbf{B} = \mu_0 \left(\mathbf{j} + \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right), \quad (1.4)$$

where μ_0 is the permeability of free space given by $\sim 1.3 \times 10^{-6}$ H/m, $\mathbf{j} = \rho \mathbf{v}$ is the current density and $\mathbf{v}$ is the average velocity of the charges. This shows that time-varying electric fields and moving charges generate magnetic fields. The second term on the right-hand side of the equation was an addition by Maxwell and in combination with Equation 1.3 shows that there are electromagnetic waves and the electric and magnetic fields propagate perpendicular to each other. Note that the second term on the right hand side is small ($\sim c^{-2}$ where c is the speed of light) and so can generally be ignored unless $\frac{\partial \mathbf{E}}{\partial t}$ is particularly large.

These equations reveal the dynamical interplay between electromagnetic fields and charged particles that underpins space plasma research and are the starting point for understanding spacecraft observations of magnetic fields.

1.5 Single Particle Motion

The approach used to study plasmas depends on the scale of the phenomenon observed. On large enough scales, in both time and space, the plasma behaves like a single conducting fluid, under which the magnetohydrodynamic (MHD) approximation is appropriate (see Section 1.6). This is commonly used for simulations of large-scale behaviour, such as the interaction between the solar wind and the magnetosphere of Saturn (e.g. Jia et al. [2012]). However, when the spatial and temporal scales associated with the plasma approach kinetic scales, the motion of individual particles cannot be ignored and instead the approach of *single particle motion* must be considered.

Under this approximation, the electromagnetic fields are treated as a

background that is unaffected by the particles (i.e. the fields generated by the particles are ignored) and so charged particle motion is only determined by these background fields. This can be assumed for instance in the context of a planetary magnetic field where the field strength is sufficiently strong as to not be significantly changed by the particles own field.

The *Lorentz force*, discovered experimentally, is given by

$$\mathbf{F} = q (\mathbf{E} + \mathbf{v} \times \mathbf{B}), \quad (1.5)$$

and expresses the forces acting on a charged particle with charge $q = ne$, where n is an integer and e is the elementary charge (charge carried by a single proton), and velocity $\mathbf{v}$ in the presence of a background electric field $\mathbf{E}$ and magnetic field $\mathbf{B}$. The force acts perpendicular to $\mathbf{v}$ and $\mathbf{B}$ but parallel to $\mathbf{E}$, and in opposite directions for ions and electrons, leaving neutral particles unaffected. It can be shown that a uniform magnetic field with zero curl does no work on a charged particle. The force it exerts will keep the particle in constant motion, changing its direction without energising it.

1.5.1 Uniform Fields

$$\mathbf{E} = 0$$

Assuming there is no electric field, it can be shown that a charged particle will gyrate with angular frequency $\omega_g = qB/m$ around a uniform magnetic field line with a radius given by

$$r_g = \frac{mv_{\perp}}{|q|B}, \quad (1.6)$$

known as the *gyroradius* of particle. A charged particle will follow a circular path around its guiding centre with a constant angular velocity and is clockwise (anticlockwise) for ions (electrons), where the magnetic field

provides the centripetal force (see Figure 1.3, where the magnetic field points out of the page and is the source of the ion and electron direction of motion). If the velocity of the charged particle has a component directed along the field its trajectory will be helical, where the *pitch angle* is the angle of the helix with respect to the magnetic field, given by $\alpha = \arctan(v_{\perp}/v_{\parallel})$ where $v_{\perp}$ and $v_{\parallel}$ are the perpendicular and parallel velocity components, respectively.

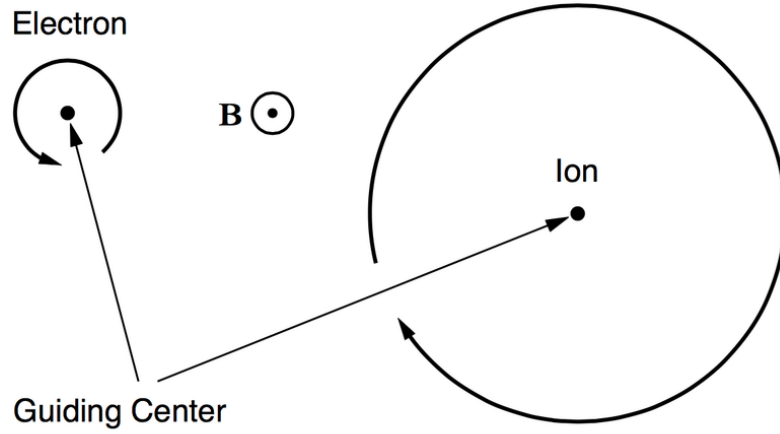


Figure 1.3: Circular motion of an ion and electron about its guiding centre in the presence of a uniform magnetic field (shown here pointing out of the page). Image from Treumann and Baumjohann [2001].

$\mathbf{E} \neq 0$

If the electric field contribution is non-negligible, the particle trajectory will drift away from symmetric gyromotion. Let us introduce a uniform electric field that is perpendicular to the magnetic field. We can for the moment ignore an electric field with a parallel component. Equation 1.5 shows that only the electric field can exert force parallel to the magnetic field and this would be oppositely directed for ions (direction of $E_{\parallel}$) and electrons (antiparallel to $E_{\parallel}$). But in a plasma, the mobile electrons would act along the

field lines to cancel the electrostatic potential. However, if $\mathbf{E}$ has a component perpendicular to the magnetic field, this can result in a particle drift.

Including an electric field perpendicular to the magnetic field when calculating the equation of motion for a charged particle introduces a drifting motion. The drift velocity due to the electric field can be written as

$$\mathbf{v}_E = \frac{\mathbf{E} \times \mathbf{B}}{B^2}, \quad (1.7)$$

and is known as the $\mathbf{E} \times \mathbf{B}$ drift and is shown in Figure 1.4. This equation shows that the drift direction is independent of charge, and so no current is induced. It is also independent of mass, implying that all particles are affected in the same way by the electric field. Observing the $\mathbf{E} \times \mathbf{B}$ drift will depend on the chosen reference frame. Switching into a frame with velocity $\mathbf{E}_\perp/B$ an observer would be unaware of this drifting motion and would see no electric field.

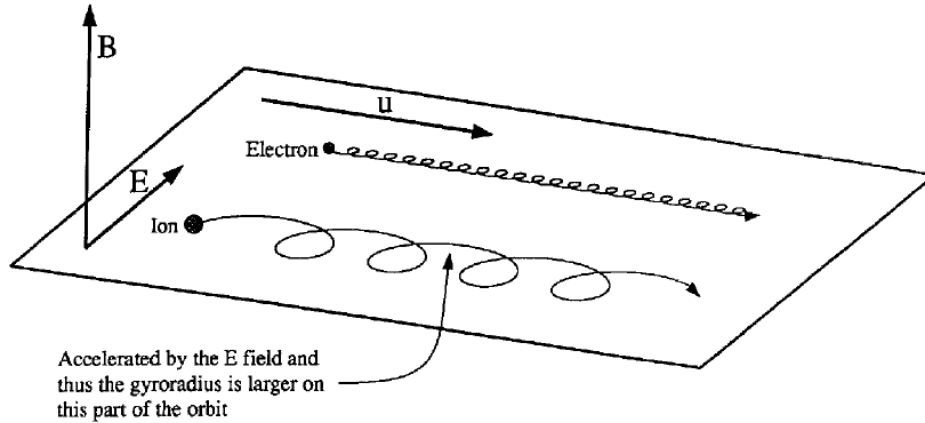


Figure 1.4: The $\mathbf{E} \times \mathbf{B}$ drift felt by particles in uniform magnetic and electric fields. Image from Voss [1991].

1.5.2 Non-Uniform Fields

Planetary magnetic fields are non-uniform, for instance exhibiting gradients in field strength and curved geometries. The drift associated with any force acting perpendicular to the magnetic field can be determined similarly to the $\mathbf{E} \times \mathbf{B}$ derivation. Re-writing Equation 1.5 in terms of the velocity associated with some general perpendicular force, assuming it is much less than the velocity of gyration of the particle, gives

$$\mathbf{v}_f = \frac{\mathbf{F} \times \mathbf{B}}{qB^2}. \quad (1.8)$$

Any force that acts perpendicular to the magnetic field can be substituted into Equation 1.8 to calculate the associated drift velocity.

Magnetic Field Strength Gradients

If there is a gradient in the magnetic field strength, charged particles will interact with varying magnetic field strengths during a gyration, reducing its gyroradius in the stronger field. A particle will experience a force

$$\mathbf{F}_\nabla = \mu \nabla B, \quad (1.9)$$

where $\mu = W_\perp/B$ is the magnetic moment of the particle and is the first adiabatic invariant, with $W_\perp$ being the component of the particle's kinetic energy perpendicular to the magnetic field. These invariants are constant provided that changes in the system are on scales greater than the parameter scales.

This implies that as a particle moves through a non-uniform field it will respond by changing its gyroradius to keep μ constant (see Figure 1.5). This ensures the flux enclosed by the gyroradius of a charged particle remains unchanged.

Hence, Equation 1.9 is the force acting on a magnetic moment in the

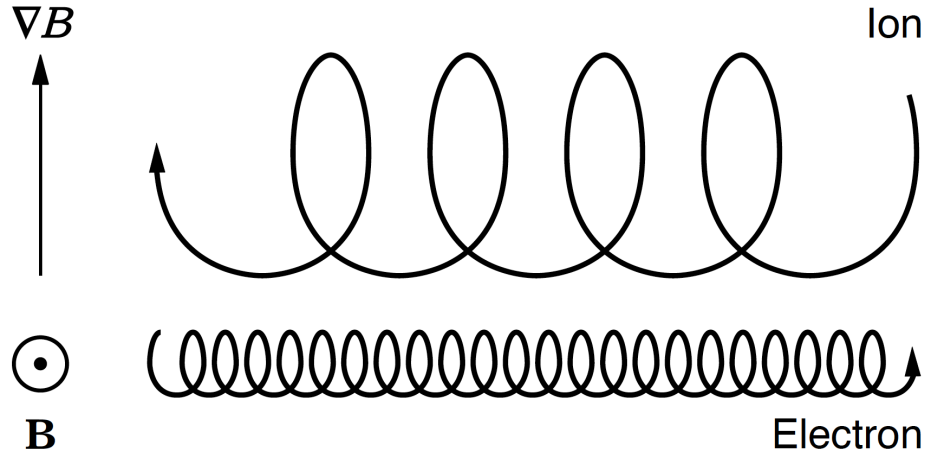


Figure 1.5: The drift felt by particles due to a magnetic field strength gradient. Image from Treumann and Baumjohann [2001].

direction of decreasing magnetic field strength. Inserting this into Equation 1.8, the gradient drift of a charged particle that acts perpendicular to both the magnetic field and the field strength gradient can be calculated. It is proportional to the perpendicular component of the particle's kinetic energy, indicating that particles with larger kinetic energies will drift faster. For a fixed energy, using Equation 1.6 the gyroradius of a particle will vary with field strength, increasing in weaker regions and decreasing in stronger regions.

Magnetic Bottle

In a planetary magnetosphere, particles near the poles, where field lines converge and the field strength is larger, will have a much smaller gyroradius. Due to the conservation of μ particles will reach a certain point along the magnetic field line before the field strength is too large and the particle will change direction and begin to gyrate back along the magnetic field line. This reflection point is called the *mirror point* and occurs at the maximum field strength for a particle with a given magnetic moment can reach

($B_{mirror} = W/\mu$ where W is the kinetic energy of the particle). Since the total energy remains constant, $W_{\perp}$ will begin to dominate over $W_{\parallel}$ to keep μ constant until $W = W_{\perp}$ and the particle stops moving along the field.

At this point, the particle's pitch angle is 90° and the particle changes direction due to the magnetic mirror force (see Figure 1.6), given by the parallel component of Equation 1.9. Substituting $v_{\perp} = v \sin \alpha$ into μ shows that particles with smaller pitch angles (within the loss cone) will mirror at lower latitudes (of higher field strength), indicating they are more likely to interact with the neutral atmosphere of a planet. In a planetary magnetic field, since the field lines end at either pole, particles are trapped bouncing between hemispheres, known as a *magnetic bottle*.

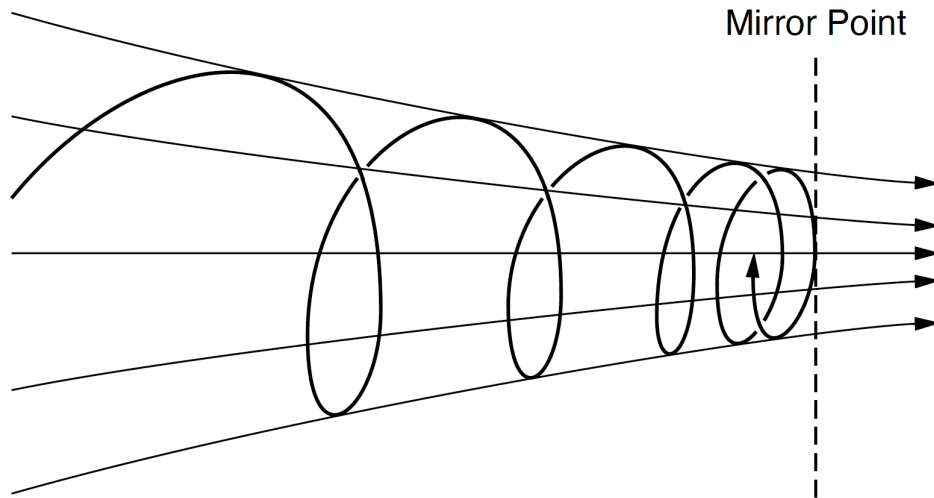


Figure 1.6: A charged particle reflecting at its mirror point as the field converges. Image from Treumann and Baumjohann [2001].

Curved Magnetic Fields

If the magnetic field is curved, such as a planetary dipole field, the charged particle will experience a centrifugal acceleration that pushes the particle

away from the centre of the radius of curvature, as seen in Figure 1.7. The centrifugal force is written as

$$\mathbf{F}_C = mv_{\parallel}^2 \frac{\mathbf{R}_C}{R_C^2}, \quad (1.10)$$

where R_C is the field radius of curvature. Inserting this into Equation 1.8 shows that the velocity is proportional to the parallel component of the particle's kinetic energy and also to $\mu \cot^2 \alpha$. A particle with a larger pitch angle will have a slower curvature drift, since μ is constant. There is also a dependence on charge indicating a current will arise due to a curved magnetic field geometry.

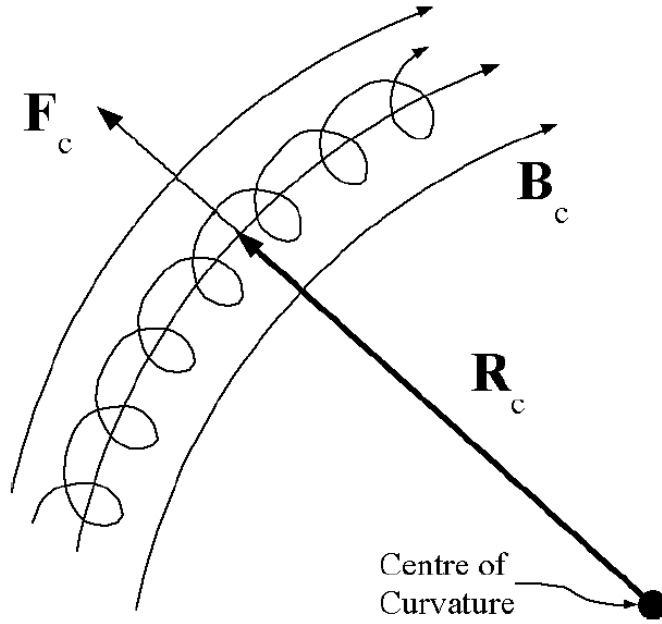


Figure 1.7: The drift felt by particles in a curved magnetic field geometry. Image from Voss [1991].

Trapped Particles and Adiabatic Invariants

The above describes how particles will behave in the presence of a planetary magnetic field that has curvature and varying strength, with field lines tied to either pole. Figure 1.8 shows the trajectory of trapped particles in Earth's magnetic field. Particles gyrate along the magnetic field, conserving the flux within the loop encircled by their gyromotion by varying their gyroradius. This occurs until a particle meets its mirror point and is reflected, bouncing between these points in each hemisphere and conserving its momentum along the field during an oscillation. These particles drift around the planet, perpendicular to both the field and force acting on it (due to both the field curvature and gradient), whilst conserving the flux contained within a closed drift shell mapped by the particles orbit.

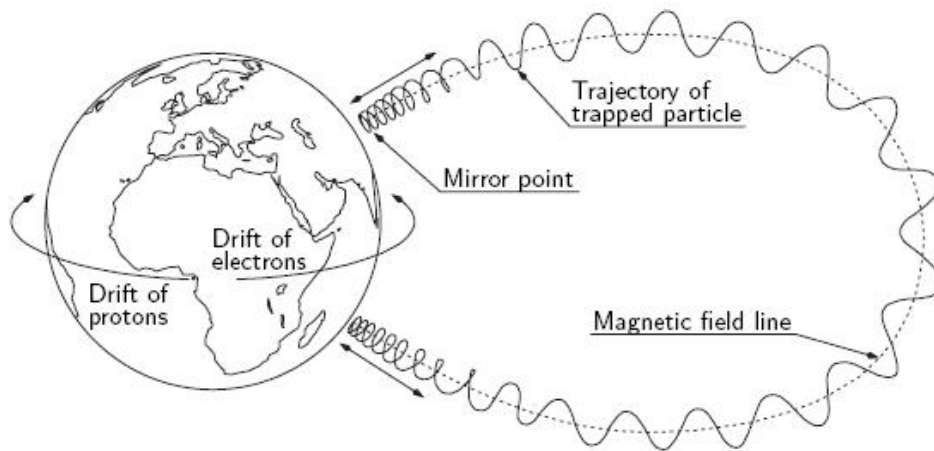


Figure 1.8: Sketch showing the trajectory of trapped charged particles in the Earth's magnetic field. Source: ESA.

Conservation of the three adiabatic invariants described above assumes that changes in the field are on scales larger (in both time and space) than the gyro-, bounce and drift motion of the particle, respectively. The structure of a planetary magnetic field will determine the trajectory of charged

particles and the currents that flow within it.

1.6 Magnetohydrodynamics

Whilst the above has discussed plasma behaviour on small scales, the large scales must be considered to understand plasmas where a magnetic field is embedded. The MHD approximation neglects the trajectories of individual particles in favour of bulk plasma properties.

Frozen-in Flow

Let us begin with a simplified Ohm's Law, given by

$$\mathbf{E} = -\mathbf{v} \times \mathbf{B} + \frac{\mathbf{j}}{\sigma_0}, \quad (1.11)$$

where $\sigma_0 = \frac{n_e e^2}{m_e \nu_c}$ is the conductivity of the plasma and ν_c is the collision frequency. Combining this with Maxwell's equations under the MHD approximation (removing the $\mathbf{E}$ term in Equation 1.4 and dropping Equation 1.1 since the plasma is charge neutral) allows for a calculation of how magnetic fields change over time in MHD. This gives us the Induction equation

$$\frac{\partial \mathbf{B}}{\partial t} = \underbrace{\nabla \times (\mathbf{v} \times \mathbf{B})}_{\text{Convection}} + \underbrace{\frac{1}{\mu_0 \sigma_0} \nabla^2 \mathbf{B}}_{\text{Diffusion}}. \quad (1.12)$$

On the right hand side of the equation, there are two components that define the evolution of the magnetic field. Which one dominates reveals the type of plasma and magnetic field interaction.

When the convection term dominates, the magnetic field and plasma flow are connected such that their motion is tied together. This is known as *frozen-in flow* [Alfvén, 1942] and is the basis for forming a boundary between magnetic fields, such as the magnetopause. In this case, the conductivity is sufficiently large (tends to infinity), or length-scales are large

enough, such that the magnetic field cannot efficiently diffuse across the plasma. This regime is known as Ideal MHD where the plasma is collisionless and infinitely conducting such that there is no resistance, simplifying Equation 1.11 to

$$\mathbf{E} = -\mathbf{v} \times \mathbf{B} \quad (1.13)$$

which shows that when there is an electric field, the plasma is moving.

The total flux through some closed loop is constant regardless of whether the surface bounded by this loop is deformed. The magnetic flux through some closed loop is written as

$$\Phi_B = \int_S \mathbf{B} \cdot d\mathbf{S}, \quad (1.14)$$

where $d\mathbf{S}$ is the area element of some surface S that is bound by a closed loop C . Taking the derivative of this gives

$$\frac{d\Phi_B}{dt} = \int_S \frac{\partial \mathbf{B}}{\partial t} \cdot d\mathbf{S} + \oint_C \mathbf{B} \cdot \mathbf{v} \times d\mathbf{l}, \quad (1.15)$$

which describes how the flux through the surface could change either due to a time varying magnetic field or because the surface is changing shape. However, by re-writing the first term using Equation 1.12 assuming infinite conductivity and using Stokes' theorem, and by using a vector identity for the second term to rearrange, shows that these two deformations to the field are equivalent but oppositely directed. Hence

$$\frac{d\Phi_B}{dt} = 0. \quad (1.16)$$

This implies that the flux through any given surface remains constant and changes in the magnetic field or surface topology will cancel each other out. The plasma and the magnetic field are coupled in their motion. The collection of field lines that bound a given surface with constant magnetic

flux is called a *flux tube*.

When the diffusion term dominates in Equation 1.12, field lines are able to diffuse through the plasma, thereby allowing charged particles to move across field lines. Here, for instance, small length-scales are required to reduce the timescales for diffusion to occur. This can allow for momentum and energy to be transferred between two magnetic media via a process known as *magnetic reconnection* where magnetic energy is converted into particle kinetic energy.

Taking the ratio of these two gives us the magnetic Reynolds number, which can be used to determine the behaviour of the plasma in a given environment. Identifying regions where these behaviours dominate identifies boundaries between separate magnetic fields and is the foundation for magnetospheric formation.

Magnetic Pressure and Tension

To further explore the relationship between plasma and magnetic fields on large scales, the magnetic forces that arise can be examined. On the large scales of MHD, the plasma has zero charge, implying the overall electric force is small. However magnetic forces are of significant importance. Taking the cross product of Equation 1.4 with $\mathbf{B}$ in the low frequency limit of MHD gives

$$\mathbf{j} \times \mathbf{B} = -\nabla_{\perp} \left(\frac{B^2}{2\mu_0} \right) - \frac{B^2}{\mu_0} \frac{\mathbf{R}_C}{R_C^2}, \quad (1.17)$$

where $\mathbf{R}_C$ is the radius of curvature vector of the magnetic field that points outward with respect to the centre of curvature as shown in Figure 1.7. Hence the $\mathbf{j} \times \mathbf{B}$ magnetic force acting perpendicular to the field can be split into two components. The first term on the right hand side of Equation 1.17 acts perpendicular to the field and can be described as a magnetic

pressure. The second hand term is antiparallel to the radius of curvature and acts to restore the magnetic field when it is curved, analogous to a restoring force and can be described as magnetic tension. These two equations reveal how magnetic fields act to restore equilibrium when perturbed.

The relative importance of the magnetic pressure to the plasma pressure can be compared by taking their ratio, known as *plasma beta*, given by

$$\beta = \frac{nk_B T}{B^2/\mu_0}, \quad (1.18)$$

where n is the plasma density, $T = T_e + T_i$ is the temperature and k_B is the Boltzmann constant. This tells us what controls the configuration of the magnetic field in a given environment. If $\beta < 1$ the magnetic pressure dominates and will act to confine the plasma. If $\beta > 1$ the plasma pressure dominates, implying the plasma can reconfigure the magnetic field.

1.7 The Solar Wind

The Sun is a 4.6 billion year old star that comprises 99.86% of our solar system mass. Its core is sufficiently hot with such high pressure that nuclear fusion occurs where hydrogen is fused into helium. This release of energy provides the heat and light from the Sun that fuels our own existence on Earth.

Figure 1.10 shows the layers of the Sun's interior. Moving from the core, energy is transferred firstly via radiation (until the tachocline), then convection (until the photosphere). The atmosphere of the Sun has three distinct layers: the photosphere, the chromosphere, and the corona that is clearly visible during an eclipse. What is a mystery is that whilst the temperature decreases from the core to the photosphere, it then increases with radial distance. The reason for this is unknown, but due to the high temperature ($\sim 10^6$ K) of the corona, the gravitational attraction of the Sun

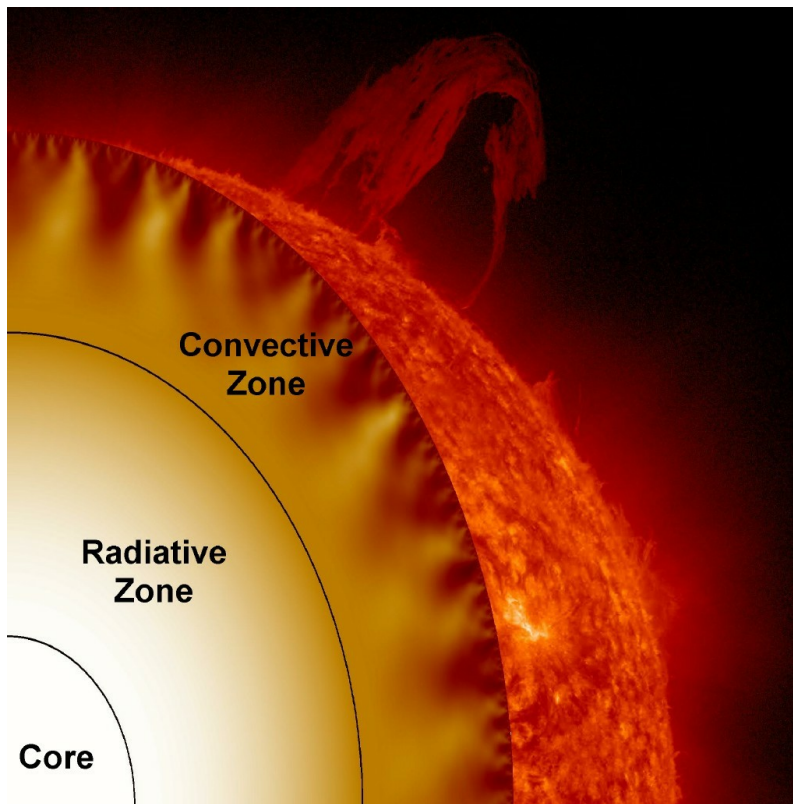


Figure 1.9: The Sun and its interior. This figure shows the core, the radiative zone and the convective zone. Above this is atmosphere of the Sun. Source: NASA.

cannot contain the atmosphere of the Sun. The transition region above the chromosphere, where the temperature and pressure rapidly increases, almost completely ionises the corona. Since the pressure difference between this and the local interstellar medium is large, the atmosphere of the Sun flows radially away from the surface of the Sun until it reaches a pressure balance and is slowed at the termination shock that encases the solar system. The Voyager 1 and 2 spacecraft crossed the termination shock in 2004 and 2007, respectively [e.g. Stone et al., 2005, Richardson et al., 2008] before they crossed the heliopause boundary and entered the interstellar medium in 2012 and 2018, respectively [e.g. Gurnett et al., 2013, Richardson et al.,

2019].

The solar wind is a continuous supersonic stream of charged particles, predominantly composed of protons and electrons, that flows outwards from the Sun. Due to the high conductivity of the solar wind plasma it drags with it the magnetic field of the Sun, known as the Interplanetary Magnetic Field (IMF). As the Sun rotates, with a period of 25.4 days, the radial flow gains an azimuthal component once the flow energy density is greater than the magnetic pressure exerted by the IMF, forming the Parker Spiral configuration [Parker, 1958b].



Figure 1.10: Sketch of the Parker Spiral, showing the Sun, the heliospheric current sheet in pink and the orbital paths of the solar system planets up to Jupiter. Source: NASA/Werner Heil.

The solar wind has an average flow speed at 1 AU (~ 150 million km, the average distance between the Sun and the Earth) of 450 km/s, with a total density of 5 cm^{-3} and field strength of 5 nT. However, the solar wind properties vary with distance from the Sun and over time. Such dynamic behaviour produces different effects for the astronomical bodies within the heliosphere.

The 11-year solar cycle shown in Figure 1.11, where the number of sunspots modulates at an 11-year frequency, arises due to reversal in polarity of the solar magnetic field. Whilst still an area of active research, there is agreement for the way in which the solar dynamo produces this cycle [Tobias, 2002]. At solar minimum, the solar magnetic field is predominantly poloidal (r, θ) where r is the spherical radial distance from the origin and θ is the polar angle. It is stable such that there are few sunspots of which most arise at high latitudes. At solar maximum, the poloidal field is wound up due to the differential rotation at the tachocline, introducing a toroidal azimuthal component (ϕ) which, coupled with coriolis effects on flux moving through the atmospheric layers, produces more sunspots close to the equator and a more dynamic solar field. The solar cycle can affect the near space magnetic environment of Saturn, for instance by reducing the production of plasma sourced from the moon Enceladus under low EUV irradiance at solar minimum [Jackman and Arridge, 2011a].

Transient solar phenomena also exhibit dynamical features that affect planetary magnetic environments. For instance, Coronal Mass Ejections (CMEs) occur when closed magnetic field loops in the corona reconnect and are accelerated into the interplanetary medium to speeds of up to 2500 km/s. These explosive structures can induce significant effects at Saturn, such as large compressions of the dayside magnetosphere [Prise et al., 2015].

The solar wind also exhibits two different types of flow, fast (~ 800 km/s) and slow (~ 400 km/s) streams. When a fast stream catches up with a slow stream, this interaction forms a structure known as a Corotating Interaction Region (CIR). A compressed solar wind region forms in the rear of the slow stream and a rarefied region forms at the rear of the fast stream. With the continued outflow of the solar wind and the development of these regions of increased dynamic pressure, CIRs could be the source of regular compressions to the Saturnian magnetosphere, compared with

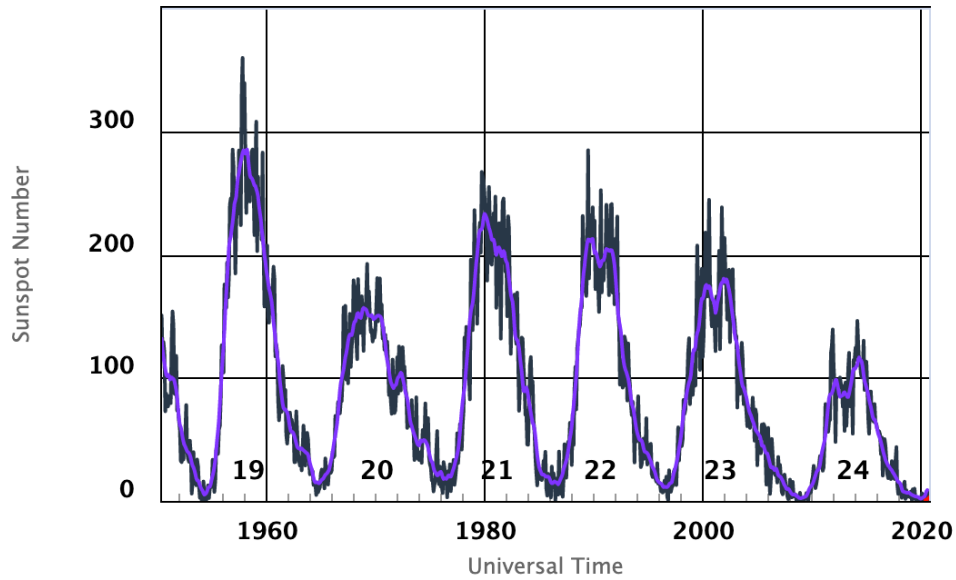


Figure 1.11: The solar cycle since 1950, showing the monthly values (black) and smoothed monthly values (purple). Image from the National Oceanic and Atmospheric Administration.

the intermittent compressions we might expect from CMEs.

1.8 Magnetospheric Formation

In a similar way to the solar wind reaching pressure balance with the interstellar medium at the heliopause, a pressure balance exists between the solar wind and a magnetised body. To begin, the general picture of magnetospheric formation will be described in terms of the Earth's magnetosphere. Figure 1.12 shows the global configuration of the currents, plasma and field structure in the terrestrial system.

The Earth's internally generated magnetic field can be viewed as dipolar to first-order approximation, with its magnetic north pole in the geographic south pole and the magnetic south pole in the geographic north pole. In a vacuum, the dipole magnetic field lines would go to infinity,

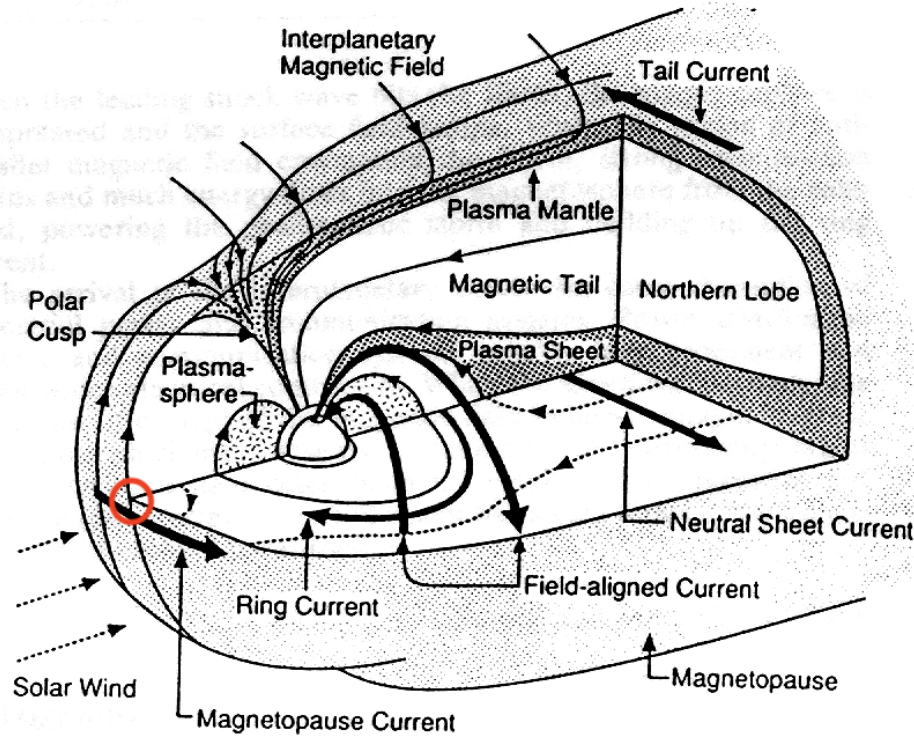


Figure 1.12: Cartoon showing the currents, plasma and fields of Earth's magnetosphere. The upstream nose standoff distance R_{SS} is highlighted in red. Image from Kivelson and Russell [1995].

with strength that goes as r^{-3} . However, the constant outflow of material from the Sun that drags the IMF with it results in an interaction between the two magnetic fields, as was initially predicted by Chapman and Ferraro [1930].

Much like a bow wave forms upstream of a boat as it ploughs through water, as the supersonic solar wind flows through the interplanetary medium, when it interacts with an obstacle like the Earth's magnetic field, a shock wave forms, known as the *bow shock*. The solar wind is travelling faster than the speed at which information can transfer via MHD waves and so a collisionless standing shock wave sits upstream of the Earth, defining

the boundary between supersonic and subsonic solar wind plasma flow. Past this shock wave, the solar wind bulk flow kinetic energy is converted into thermal and magnetic energy, producing a higher field strength and plasma density but reducing the bulk flow velocity, allowing it to flow around the Earth's magnetosphere, forming the *magnetosheath*.

The frozen-in theorem states that the solar wind magnetic field and Earth's magnetic field cannot mix. The solar wind flows around the Earth and forms a cavity within the IMF known as a *magnetosphere*, with the boundary between the two regions called the *magnetopause*. Due to a non-zero curl of $\mathbf{B}$ between the IMF and the Earth's magnetic field, currents flow along the boundary by Equation 1.4. Solar wind protons and electrons half gyrate at the boundary in opposite directions, generating currents that act to contain the planetary field.

The first interaction between the Earth's field and the solar wind is at the upstream subsolar standoff distance of the magnetopause. It is a proxy for magnetosphere size and is given by

$$R_{SS} \approx \sqrt[6]{\frac{2B_0^2}{\mu_0 \rho_{sw} v_{sw}^2}}, \quad (1.19)$$

where B_0 is the magnetic moment of the magnetised body and ρ_{sw} and v_{sw} are the solar wind density and velocity, respectively. The standoff distance is shown in Figure 1.12. For Earth, this value is usually close to $10R_E$, where $R_E = 6371$ km. However, Chapter 2 will show that for the outer planets not only is this value larger (in units of planetary radii), but is more variable due to additional internal pressures that modify the assumptions made when calculating Equation 1.19.

A breakdown of the frozen-in theorem can occur at the dayside magnetopause under certain conditions (such as high magnetic shear) and the IMF can reconnect with the closed terrestrial magnetic field lines. These newly opened field lines have one foot anchored to the Earth's ionosphere

and one in the solar wind, allowing solar wind plasma to enter the Earth's magnetosphere and interact with the atmosphere. These field lines are dragged along the ionosphere with the solar wind flow to the nightside and close when the field lines reconnect across the *magnetotail current sheet* that separates the two lobes in the magnetotail. This process accelerates plasma planetwards whilst also expelling plasma and flux from the system. The field lines moving towards Earth convect back to the dayside and the cycle restarts. This global convection pattern of magnetic flux is known as the Dungey cycle [Dungey, 1961] and is thought to be the dominant mass transport mechanism for the Earth's magnetosphere.

Particles trapped in the magnetosphere of Earth, either sourced from the ionosphere or the solar wind, that are gradient and curvature drifting with ions and electrons drifting in opposite directions (by Equation 1.8), form the *ring current*.

Large-scale plasma motion in the magnetosphere of the Earth is driven by two electric fields. The first is the convection electric field, given by Equation 1.13 and is due to the concurrent drift of plasma frozen-in to the magnetic field. The convection of plasma towards the Earth following nightside reconnection drives a dusk-to-dawn cross-tail electric field. However, close to the Earth, motion is not driven by the interaction between the planetary field and the solar wind but instead by the rotation of the planet. Collisions between neutral atmospheric particles and ionospheric charged particles accelerates the magnetic field and plasma towards corotation. However, this process is hindered by the finite conductivity of the ionosphere (see Section 2.3.2 for full description). At the Earth, the corotation electric field dominates the convection electric field close to the planet, forming a region of corotating plasma known as the *plasmasphere*, shown in Figure 1.13.

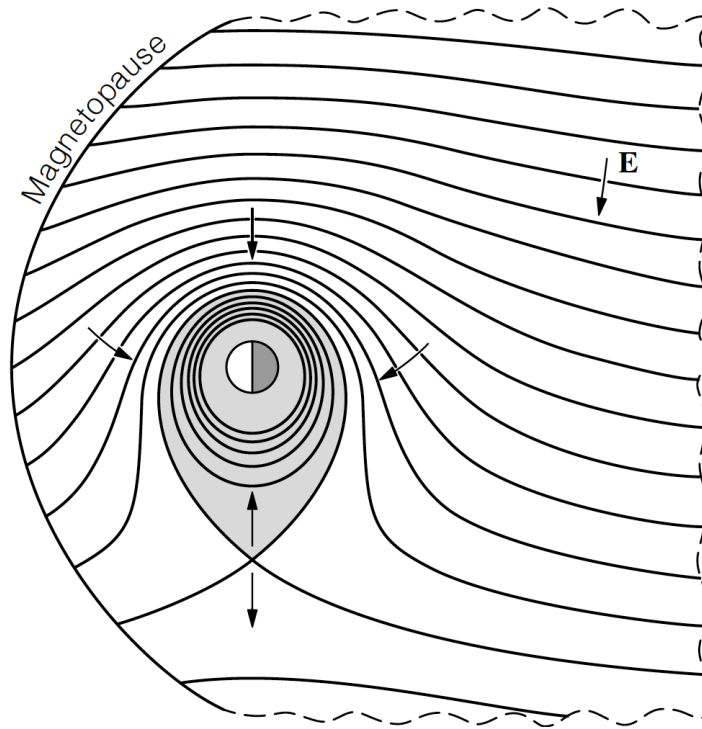


Figure 1.13: Electric equipotential contours that show the two different regions within the magnetosphere of Earth, shown in the equatorial plane. Close to the planet, the shaded region shows where corotation dominates and the electric field $\mathbf{E}$ points towards the Earth. Outside of this region, convection dominates. Figure from Treumann and Baumjohann [2001].

1.9 Summary

This chapter has introduced the fundamental plasma physics concepts required for understanding the behaviour of plasmas in a planetary magnetic field. The general picture of magnetospheric formation, structure and dynamics presented in this chapter is a good approximation at Earth. However, at Saturn the picture is complicated by some key differences between the two systems, such as the internal magnetic field strength, planet rotation speed, distance from the Sun and the presence of an internal plasma source at Saturn. For instance, the stagnation point between the two elec-

tric fields shown in Figure 1.13, where the equipotential contour crosses itself, depends on the rotation rate of the planet, planetary field strength, planet radius and the convection electric field strength. Hence, this transition will occur at larger radial distances for rapidly rotating planets and so our picture of magnetospheric plasma motion will differ.

Therefore, the simplified overview presented here in terms of the Earth will be built upon for the Saturn system.

Chapter 2

The Saturn System

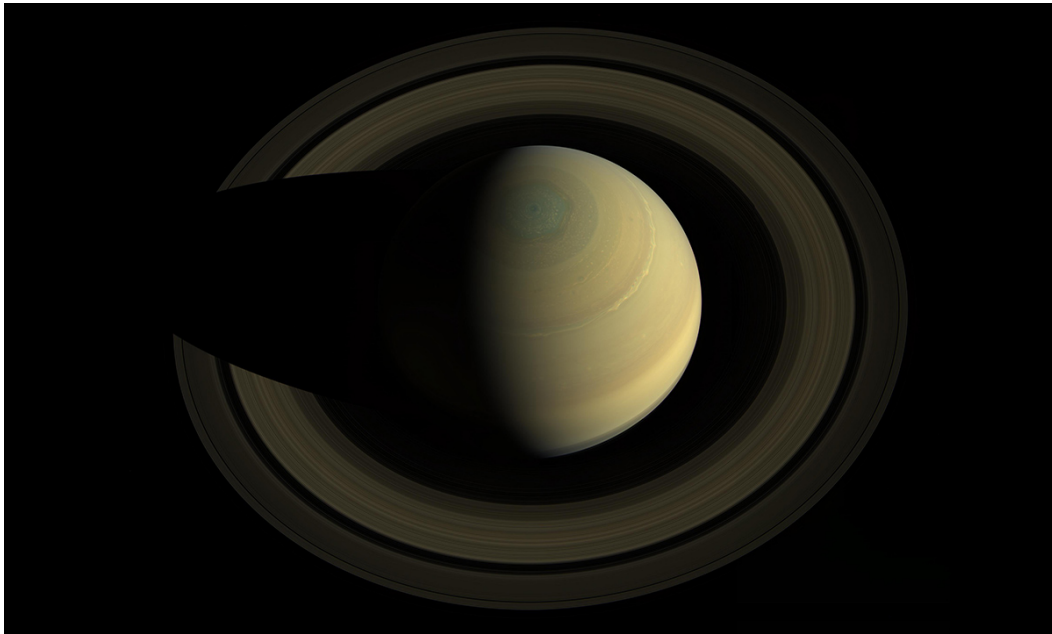


Figure 2.1: Composite image of Saturn in natural colour taken by the Cassini imaging science subsystem. Source: NASA/JPL-Caltech/SSI/Cornell.

Saturn has captured the imagination of humans for centuries, primarily due to its fascinating ring system. Saturn was observed by eye as early as

the Ancient Greeks, but it was first observed using a telescope by Galileo in the 17th Century. However, it was not until later that century that Christiaan Huygens identified the rings. Whilst these discoveries were made observationally from Earth, Saturn has now been visited by four spacecraft in total, providing us with rich in-situ datasets. The first three of these visits were flybys by Pioneer 11, Voyager 1 and Voyager 2 between 1979 and 1981. The Cassini spacecraft is the only orbital mission of Saturn so far. It executed orbital insertion in 2004 and ended with a fateful plunge into the atmosphere of Saturn in 2017.

In this chapter we will discuss the Saturn system with a focus on its magnetosphere. We will outline the key research to date regarding its large-scale structure that will support the work presented in later chapters.

2.1 Saturn Composition

Close to 4.5 billion years ago our solar system began to form. The accretion of hydrogen and helium from the solar nebular onto a rocky core was the basis of formation for Saturn. Saturn is the second largest planet in our solar system by both size and mass and orbits the Sun at 9.6 AU. The rocky core of Saturn is approximately ~ 10 times the mass of Earth. Surrounding this core there is a layer where the pressure is sufficiently high such that hydrogen is in a liquid metallic state [Hubbard et al., 2009]. This is where the magnetic field of Saturn is believed to be generated (see Section 2.3.1). Moving further from the core, the pressure and temperature decreases such that hydrogen enters the gas state. The ‘surface’ of Saturn is defined as the region where the pressure is equal to 1 bar level (the atmospheric pressure on Earth at sea level), given by $R_S = 60,268$ km from the centre of Saturn. This is the equatorial radius of Saturn, given that the gas giant is oblate with a radius varying by 10% between the poles and the equator.

Since Saturn has no clearly visible surface features, the rotation period cannot be calculated by observing a singular feature as it rotates with the planet. Modulations of radio emissions from Saturn, known as Saturn Kilometric Radiation (SKR), detected by the Voyager spacecraft were initially used to determine a rotation rate [Kaiser et al., 1980, Desch and Kaiser, 1981]. However it was later discovered this rate changes and is related to periodic modulations that vary with season (see Section 2.3.4). Most recently, the length of a day at Saturn has been determined using perturbations of the rings by the varying gravitational field of Saturn, finding the day to be 10hrs 33mins 38secs, faster than the range of values found with SKR [Mankovich et al., 2019].

The thermosphere of Saturn has a temperature of 586 K at high latitudes and 340 K at lower latitudes, and then decreasing towards the equator [Brown et al., 2020]. These values are significantly larger than would be expected from solar energy alone. This problem, known as the ‘energy crisis’, has now been observed at all the outer planets. A potential solution could be auroral heating, whereby the closure of currents at high latitudes heats the upper atmosphere and this heat is redistributed to lower latitudes via gravity waves [Melin, 2020]. The ionosphere is the upper atmospheric layer ($\sim 300 - 5000\text{km}$ in altitude, measured from the 1 bar altitude) of charged particles that are ionised predominantly by solar extreme ultraviolet radiation [Nagy et al., 2009]. The ionosphere then couples the planet to the magnetosphere, transferring angular momentum from the planet via field-aligned currents to the magnetospheric plasma (see Section 2.3.2).

2.2 The Rings and Moons

The rings of Saturn lie between $1.11 R_S$ and $2.27 R_S$ and are composed predominantly of ice grains, ranging in size from $\sim \mu\text{m}$ to $\sim 10\text{m}$ with the average thickness of the rings being less than 100m [Cuzzi et al., 2009].

The rings are named in order of discovery, rather than distance from the planet, and range from the A ring to the G ring. The source of the rings is still unknown, but could be due to a comet breaking up on approach to Saturn, or could be the remnants of a previous moon [Cuzzi et al., 2009]. The diffuse E ring was known to be composed of water ice with ring particles concentrated near the orbit of Enceladus from the Voyager flybys [Stone and Miner, 1981]. However it was the Cassini mission that discovered the small moon Enceladus had plumes of water vapour [Dougherty et al., 2006, Hansen et al., 2006] that were the primary source of this ring [Spahn et al., 2006].

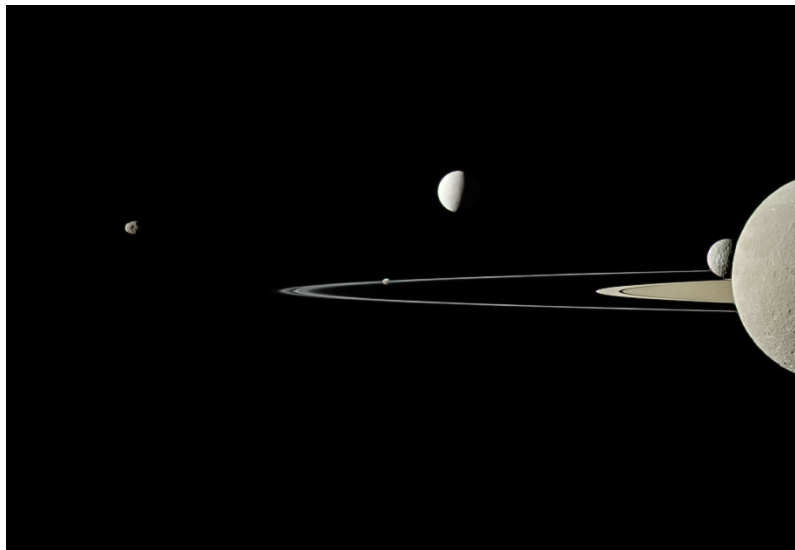


Figure 2.2: Image showing five of Saturn's moons and its outer rings. Moving from left to ring: Janus, the F-ring, Pandora, Enceladus, the A-ring and Encke Division, Mimas and Rhea. Source: NASA/JPL-Caltech/Space Science Institute.

The more opaque rings cast a shadow on Saturn, thus suppressing photoionization when it is blocked, with enhanced ionization of the ionosphere occurring in the Cassini division between the A and B rings [Ida, 2019]. This gap arises due to the resonance between the rings and the moon Mi-

mas. Some of the ice grains are charged, for instance via photoionisation, and it has been observed that small charged ring particles stream into the ionosphere along field lines as ‘ring rain’ [O’Donoghue et al., 2013].

There are currently 82 known moons that orbit Saturn, not including the moonlets within the rings. The largest of these is Titan with a radius of 2574 km, making it larger than Mercury, and is the only known moon in the solar system with an appreciable atmosphere [Brown et al., 2010]. The second largest is Enceladus which provided one of the key Cassini discoveries of geysers emitting water vapour from its south pole [Dougherty et al., 2006, Hansen et al., 2006]. Enceladus is the primary source of plasma within the magnetosphere of Saturn [Dougherty et al., 2009] and has a vital role shaping the large-scale structure of the system.

2.3 The Saturnian Magnetosphere

A sketch of the magnetosphere of Saturn is shown in Figure 2.3, showing its large-scale structure and highlighting key features that modify it. The remainder of this chapter will discuss these features, including the internally generated magnetic field, the current sheet and associated magnetodisc geometry, the magnetopause boundary and the ubiquitous planetary period oscillations.

2.3.1 Internal Magnetic Field

Intrinsic magnetic fields reveal the history of a planet and allow us to ‘look’ into the interior [Stevenson, 2003]. The magnetic field of Saturn is probably generated by liquid metallic hydrogen [Weir et al., 1996, Zaghoo and Silveira, 2017] in its outer core that surrounds a rocky core. To generate an intrinsic field, the rotation of a body coupled with the convection of conducting fluid generates an electric current, which in turn induces a magnetic field, known as dynamo action [Parker, 1955, Moffatt, 1978]. However, at

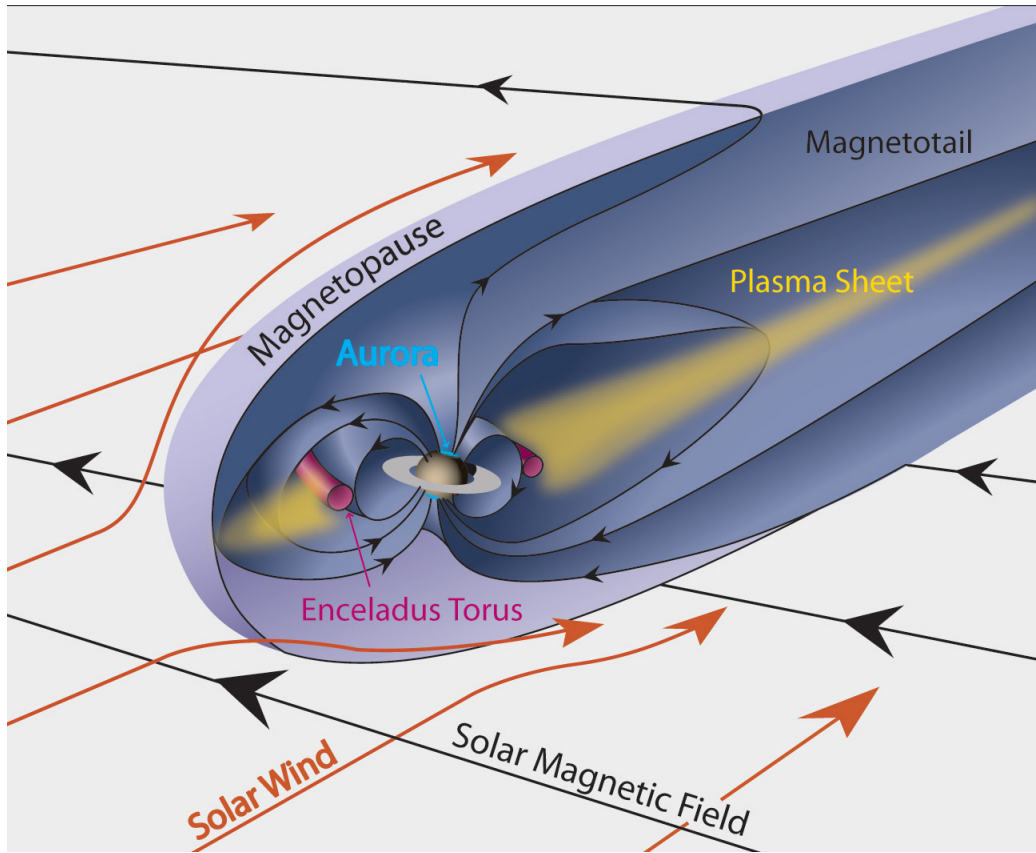


Figure 2.3: Sketch showing the magnetosphere of Saturn embedded within the solar wind (red arrows) and Interplanetary Magnetic Field (IMF - black arrows). The key features, including the magnetopause, magnetodisc structure and current/plasma sheet are shown. Credit: Fran Bagenal and Steve Bartlett.

Saturn there is an almost negligible tilt of 0.0095° and the field is highly axisymmetric [Dougherty et al., 2018]. This configuration is at odds with our current knowledge of dynamo theory, since Cowling's theorem states that no axially symmetric motion can maintain an axisymmetric magnetic field [Cowling, 1933]. The generation of the planet's axisymmetric field cannot be explained by a dynamo action suggesting a different mechanism is required. A possible solution is that there is a stably stratified and con-

ducting layer above the dynamo that is differentially rotating and essentially axisymmetrizes the field [Dougherty et al., 2018]. The lack of a tilt also prevents the detection of the planet’s internal rotation rate from the magnetic field.

There has been no detectable secular variation of the Saturn field, compared to for instance the Earth whose first three magnetic moment terms appear to vary by 20 nT a year [Cao et al., 2011]. The internal field of Saturn has a surface field strength $\sim 21,000$ nT, less than the Earth’s, and has its north pole in the geographic north pole, in the opposite sense compared to Earth. There is also a significant offset of the magnetic equator of Saturn of $0.047 R_S$ [Dougherty et al., 2018].

To model the internal magnetic field of Saturn, a spherical harmonic expansion of the magnetic potential is used [Chapman and Bartels, 1940]. To begin, we work in the region close to the planet, but outside the dynamo region, where we can assume that there are no currents and that the field is approximately steady state, such that Equation 1.4 becomes $\nabla \times \mathbf{B} = 0$. A curl-free vector can be represented as the gradient of a scalar potential, so a magnetic field in a current free region is given by $\mathbf{B} = -\nabla\Psi$ with the negative sign being convention for the direction of the magnetic field. Since the magnetic field is divergence free, we find that $-\nabla^2\Psi = 0$. Therefore, a solution for the scalar potential can be found in terms of spherical harmonics, given in spherical coordinates by

$$\Psi(r, \theta, \varphi) = R_p \sum_{n=1}^{\infty} \sum_{m=0}^n \left(\frac{R_p}{r} \right)^{n+1} P_n^m(\cos \theta) (g_n^m \cos m\varphi + h_n^m \sin m\varphi), \quad (2.1)$$

where, in the case of a planetary magnetospheric magnetic field, r represents the radial distance from the planet’s centre, θ is the colatitude, measured down from the north pole, and φ is the azimuth measured positively eastwards in the direction of rotation, R_p is the radius of the planet, m is

the order and n is the degree (both positive integers) of the expansion, P_n^m are the Schmidt normalized Legendre functions and g_n^m and h_n^m are Gauss coefficients. The Gauss coefficients represent the changing topology of the internal field and the extent to which this is influenced by each mode. The Legendre functions being normalised provides clarity when comparing each term, because we only need to observe the magnitude of the Gauss coefficients to understand their significance. We start at $n = 1$ since we cannot have $n = 0$ (no monopoles). The $1/r^{n+1}$ dependence implies that the higher order terms rapidly become negligible as our radial distance increases. A matrix scalar inversion method is employed to calculate the best-fit Gauss coefficients for the internal field [e.g. Dougherty et al., 2018]. Since we rely on in-situ spacecraft measurements to calculate the scalar potential given by Equation 2.1, which is not unique, data from multiple trajectories with significant spatial coverage are required [Dougherty et al., 2009]. Throughout the era of spacecraft exploration at Saturn, different internal field models have been calculated using this technique, and the associated model fitted parameters are shown in Table 2.1.

	Z_3 [Connerney et al., 1982]	P_{1184} [Davis and Smith, 1986]	Cassini SOI [Dougherty et al., 2005]	Cassini 11 [Dougherty et al., 2018]
g_1^0 (nT)	21,535	21,140	21,084	21,140
g_2^0 (nT)	1642	1600	1544	1581
g_3^0 (nT)	2743	2260	2150	2260
z_0 (R_S)	0.038	0.038	0.037	0.047

Table 2.1: Comparing the first three terms and northward offset of the magnetic equator for internal magnetic field models calculated throughout the era of spacecraft exploration of Saturn, going forward in time from left to right using data from Pioneer, Voyager 1 and 2, Cassini orbital insertion and Cassini end-of-mission.

The lowest order term of the spherical harmonic expansion, with $m = 0$,

is the dipole term and so substituting this potential into Equation 2.1 allows the calculation of the magnetic field components for a dipole field. The first degree terms, when $n = 1$, can be used to calculate the magnetic moment and tilt of the dipole. The g_1^0 coefficient represents a dipole with its magnetic moment pointing along the rotation axis, centred at the planet's core. If we suppose this is the Z-axis, the g_1^1 and h_1^1 terms are dipoles with magnetic moments that lie along the X-axis and Y-axis, respectively, such that the magnitude of the sum of these moments is the total magnetic moment of the planetary dipole, given by

$$M = |\mathbf{M}| = \frac{4\pi R_p^3}{\mu_0} \sqrt{(g_1^0)^2 + (g_1^1)^2 + (h_1^1)^2}, \quad (2.2)$$

which shows that the model components identified for an internally generated field will define the azimuthal and dipole tilts, the latter of which is given by

$$\lambda_0 = \cos^{-1} \left(\frac{g_1^0}{\sqrt{(g_1^0)^2 + (g_1^1)^2 + (h_1^1)^2}} \right), \quad (2.3)$$

as well as the north/south displacement of the dipole equator, given by

$$z_0 = \frac{g_2^0}{2g_1^0}. \quad (2.4)$$

It has been found that the internal field of Saturn is highly axisymmetric, implying there is no azimuthal dependence [Dougherty et al., 2018, Cao et al., 2020]. Hence only the zonal terms where $m = 0$ are used. The h_n^m coefficients identically vanish due to the $\sin m\varphi$ term in Equation 2.1 whilst the g_n^m coefficients have no dependence on the longitude since the $\cos m\varphi$ term equals to one in Equation 2.1. The tilt given by Equation 2.3 is thus zero.

During the Grand-Finale phase of the Cassini orbital mission (see Sec-

tion 3.1 for description), a variable and unexpected ~ 20 nT B_ϕ signature was observed near closest approach [Dougherty et al., 2018]. However, this was not a signature due to the internal field, shown for instance by the lack of radial dependence, and is instead suggested to be a signature of interhemispheric field-aligned currents (FACs) that map between the ionosphere and the D-ring [Khurana et al., 2018, Provan et al., 2019a, Agiwal et al., 2021].

2.3.2 The Magnetodisc

A key discovery by the Cassini spacecraft came from an unexpected source - the small moon Enceladus. This tidally-locked moon, with a radius of 252 km, orbits Saturn at $3.95 R_S$, was not believed to be geologically active before the Cassini mission. In 1981, during a flyby the Voyager spacecraft saw that the ice-covered surface of Enceladus was smooth [Smith et al., 1981] and it was known that the moon orbited within the diffuse E-ring [Stone and Miner, 1981]. First evidence of Enceladus being the source of the E-ring came when magnetic field signatures during a flyby hinted towards an atmosphere surrounding the moon [Dougherty et al., 2006]. However, on closer flybys, it was found that instead of a sustained global atmosphere, there are geysers in the southern hemisphere of the moon [Dougherty et al., 2006] that were emitting water vapour [Hansen et al., 2006], showing the moon to be the dominant source of the E-ring [Spahn et al., 2006]. The plumes are shown in Figure 2.4. Tidal heating due to resonance with the moon Dione is believed to be the energy source that keeps the ocean liquid below its ice surface [Iess et al., 2014].

Neutrals are estimated to be emitted from the Enceladus plumes at a rate of $\sim 70 - 750$ kg/s, with a rate of plasma production of $\sim 12 - 250$ kg/s [Bagenal and Delamere, 2011]. The rate is significantly less than the ~ 1 tonne/s production rate of plasma from Io at Jupiter, with a greater plasma/neutral imbalance observed primarily due to the slower rotation

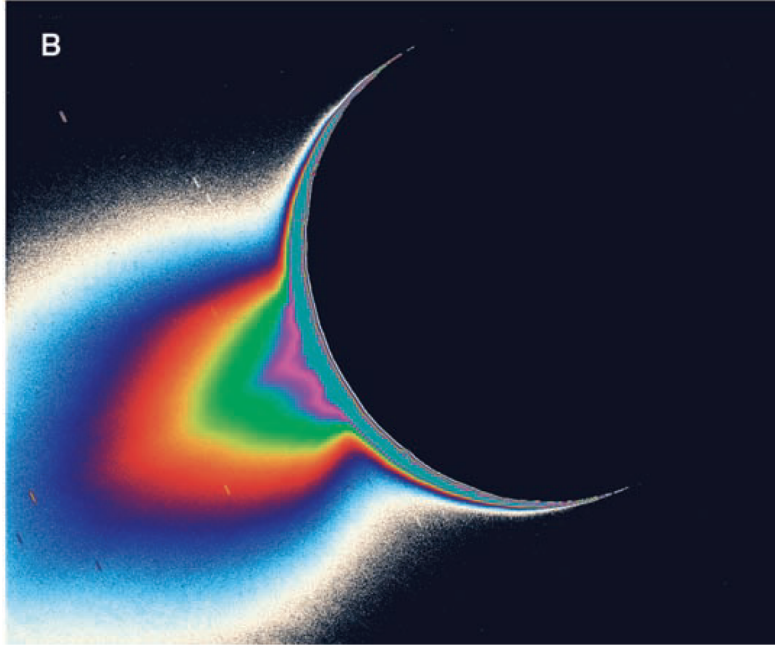


Figure 2.4: An image of Enceladus' plumes, captured by the Imaging Science Subsystem onboard Cassini, with false colouring for visibility. Image from Porco et al. [2006].

of Saturn, resulting in a lower pickup energy [Delamere et al., 2007]. A neutral cloud surrounds Saturn which over time becomes ionised through charge exchange, electron impact ionization and photoionization.

The newly produced plasma locks onto the local magnetic field lines. Due to the fast ~ 10.6 hrs rotation rate of Saturn, the plasma is centrifugally confined to the equator [Gledhill, 1967], radially stretching the dipolar field outwards into the characteristic 'magnetodisc' geometry. The equatorial layer of plasma is known as the magnetodisc current sheet, or simply the current sheet. The thermal heavy water group ions sourced from Enceladus are denoted as W^+ and include O^+ , OH^+ , H_2O^+ , and H_3O^+ , with mass per charge ratios ranging from 16 to 19 [Waite et al., 2006, Bagenal and Delamere, 2011].

The stress balance acting to keep the magnetodisc in equilibrium is

given by

$$\mathbf{j} \times \mathbf{B} = \nabla p - nm_i \omega^2 \rho \mathbf{e}_\rho, \quad (2.5)$$

where ω is the angular velocity of the plasma and ρ is the cylindrical radial distance from the axis. This equation shows the force balance required between magnetic force (left hand side, which includes the magnetic pressure gradient and curvature force) the plasma pressure gradient (first term on the right hand side), and the centrifugal force (second term on the right hand side) to maintain the disc.

We can describe a magnetodisc using 2-D equilibrium models that include centrifugal force and plasma thermal pressure to solve the force balance of Equation 2.5. These models can be used to infer global distributions of current in a magnetodisc. This model formalism was developed by Caudal [1986] at Jupiter and further modified for Saturn by Achilleos et al. [2010] and Chou and Cheng [2010]. Outputs from the Achilleos et al. [2010] magnetodisc model will be used in Chapter 6 to analyse how disc-like the field is in different regions of the Saturnian magnetosphere.

The highly stretched magnetic field and overall outward force acting on the plasma is associated with an azimuthal current flowing within the equatorial sheet of plasma, providing the inward directed $\mathbf{j}_\phi \times \mathbf{B}$ Lorentz force that supports the radial stress balance of the magnetodisc [Southwood and Kivelson, 2001]. The azimuthal current loop carried by the plasma produces a solenoidal magnetic field that is northward near the current sheet inner edge such that it depresses the planetary magnetic field close to the planet, and southward at its outer edge, adding to the background field.

Radial currents $\mathbf{j}_r$ in the disc are a sign of the azimuthal stress balance between the plasma and the rotating field. In the presence of a plasma source and the radial transport of plasma away from its source, complete corotation cannot be achieved [Hill, 1979]. As the plasma is produced and

Figure 1.13). However, at Saturn the rapid rotation of the planet implies that the corotation electric field dominates a larger region of the magnetosphere and the solar wind electric field modifies dynamics down the tail Mitchell et al. [2009]. Hence we often describe the Saturnian magnetosphere as rotationally-dominated, whilst the dynamics of Earth's magnetosphere are driven by the solar wind.

Mass Transport and Loss

Whilst the radial outflow of Enceladus-sourced plasma from the inner magnetosphere and its implications on corotation has been discussed, the transport mechanism by which this can occur has not been explored. In the low plasma beta ($\beta < 1$) of the inner magnetosphere, plasma is radially transported via an interchange instability with the more tenuous hot plasma population in the outer magnetosphere [Gold, 1959], similar to the Rayleigh-Taylor instability, but gravity is replaced with the centrifugal force. These intermittent events preserve the global magnetic field structure, thus satisfying the plasma beta conditions, whilst radially transporting plasma outwards. Multiple catalogues of injection events, parcels of hot tenuous plasma within the colder dense plasma population in the inner magnetosphere, have been made with the Cassini data [e.g. Lai et al., 2016, Azari et al., 2018] that have found the peak of events occurring between 7-9 R_S and predominantly on the nightside.

At larger radial distances, plasma pressure begins to dominate ($\beta > 1$) such that the plasma can modify the magnetic field structure and the magnetic pressure can no longer balance the centrifugal forces of the plasma. The magnetodisc is no longer in steady state and the ballooning instability (see Figure 2.6), given by $p_{\parallel} > p_{\perp} + B^2/\mu_0$, where p is the plasma pressure and the second term on the right-hand-side is the magnetic field tension, identifies the point at which the force balance collapses and plasma can break off from the disc [Southwood and Kivelson, 2001, Kivelson and

Southwood, 2005]. As the magnetic field rotates around the planet on the dayside it is confined by the magnetopause, prohibiting this from occurring. On the nightside, the field stretches freely into the tail, eventually reconnecting the closed field lines and allowing plasma to be lost in the magnetotail, a process known as the Vasyliūnas cycle [Vasyliunas, 1983]. It has been argued that a region of mass-depleted flux tubes following nightside reconnection should reside between the magnetodisc and magnetopause in the dawn sector for rotationally-dominated magnetospheres [Kivelson and Southwood, 2005]. Whilst this has been observed at Jupiter, this has yet to be confirmed at Saturn [Went et al., 2011b]. Magnetodisc reconnection has also been observed on the dayside [Delamere et al., 2015, Guo et al., 2018a,b] showing that this instability is not restricted to the nightside.

Closure of open flux via Dungey-type reconnection, as described in Section 1.8, has also been observed at Saturn following solar wind compression [e.g. Thomsen et al., 2015]. This occurs in addition to the Vasyliūnas-type mass loss mechanism described above, differentiated in the data by the return flow plasma composition [Badman and Cowley, 2007]. However, the size of plasmoids measured by Cassini (and inferred mass content) appears to be too small to balance the mass production rate of Enceladus [Jackman et al., 2014]. This could indicate the dominance of other mechanisms for the transfer of energy, such as small-scale and frequent ‘drizzle-like’ reconnection [Delamere et al., 2015] or Kelvin-Helmholtz instabilities along the magnetopause playing a greater role than Dungey-type reconnection [Masters, 2018].

Dependence on System Size

The magnetodisc geometry that the current sheet supports was not initially identified at Saturn in the magnetometer data of the early flyby missions, except at dawn [Smith et al., 1980], implying the current sheet was too weak to distort the field entirely. However, Arridge et al. [2008b] showed that this

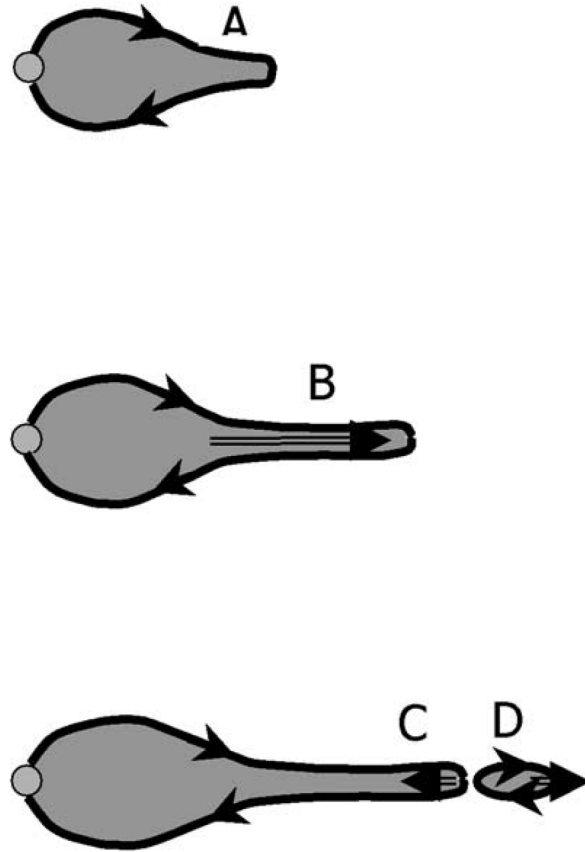


Figure 2.6: The stages of ballooning of the magnetodisc until the field reconnects and plasma is lost from the system. Image from Kivelson and Southwood [2005].

phenomena is observed at all local times (fixed reference frame going from midnight on the far side of Saturn to noon on the near side of Saturn with respect to the Sun) under expanded conditions, when the magnetopause standoff distance is greater than $23 R_S$. Close to the planet ($< 15 R_S$) the internally generated magnetic field determines the field geometry and it is quasi-dipolar. On average, for radial distances $> 15 R_S$ and when the system is expanded, the current sheet and equatorial plasma radially stretch

the magnetic field into a magnetodisc.

The strength and size of the current sheet varies with system size [Bunce et al., 2007, Bunce et al., 2008, Arridge et al., 2008b]. Figure 2.7 shows that as the system expands, the outer edge of the current sheet moves radially outwards and the total current flowing in the disc increases. Bunce et al. [2008] showed that the inertial drift of the heavy ions associated with the centrifugal force felt by the rotating plasma and resultant inertia current is the dominant contribution to the current sheet magnetic moment, assuming at least partial corotation enforcement via ionospheric torque [Bunce et al., 2007, Bunce et al., 2008]. Further work has found that whilst the inertia currents dominates in the inner and middle magnetosphere, the currents associated with the hot plasma pressure gradient become more important in the outer magnetosphere particularly at midnight and dawn, most likely due to processes related to reconnection in the tail [Kellett et al., 2011, Sergis et al., 2017].

Due to the 26.7° obliquity of Saturn, the angle between the solar wind flow and the planetary equator varies with time. The stress acting on the magnetopause by the solar wind at equinox acts to compress the magnetosphere, but during solstice conditions the angle is no longer perpendicular such that the solar wind forcing displaces the current sheet out of the equator. The global morphology of the current sheet resembles a bowl shape around the planet [Arridge et al., 2008a] that is either above or below the rotational equator depending on season. The distance at which the current sheet is hinged out of the dipole equator R_H varies between $16 - 32 R_S$ [Arridge et al., 2011, Carbary et al., 2015, Agiwal et al., 2020] and will depend on how much the solar wind is compressing the system.

Modelling the Current Sheet

A widely used model of the magnetodisc current sheet was developed for Jupiter by Connerney et al. [1981a], and later applied to Saturn [Connerney

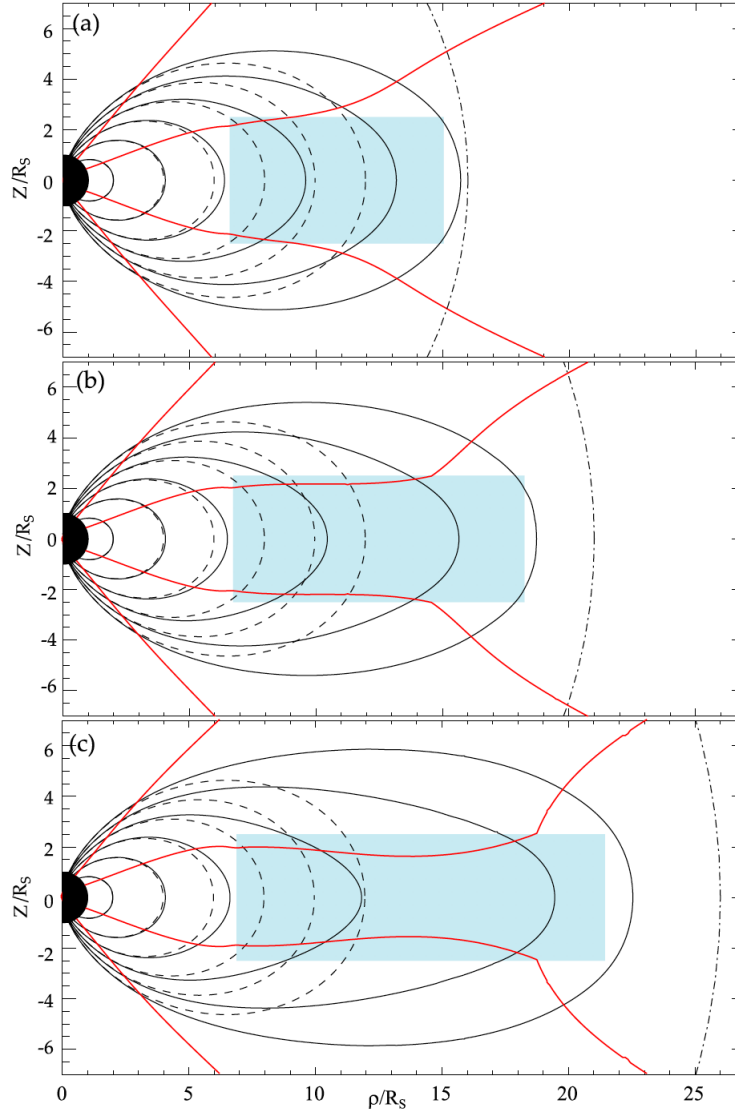


Figure 2.7: Plot showing the magnetodisc increasing with system size in a cylindrical $\rho - Z$ plane. The magnetodisc field lines are in black, with dipole field lines shown as dashed black lines, the blue box is the current sheet and the dot dashed line shows the magnetopause. The red lines bound the region where the angle between the magnetic field and the equatorial plane is 30° or less. Plot from Bunce et al. [2008].

et al., 1981b, 1983] known as the CAN model. In Chapters 4 and 5 this model is employed and will be briefly outlined here.

The model consists of a three-dimensional annulus of current, with the planet at the center of the annulus, that has some constant half-thickness D , inner edge R_1 and outer edge R_2 , given in units of Saturn radii, and a current intensity parameter $\mu_0 I_0$, given in units of nanotesla. We begin by calculating the field due to a current sheet that has an inner edge but goes to infinity. Assuming that the current flowing is purely azimuthal, its magnetic field can be described in terms of a potential, where $\mathbf{B} = \nabla \times \mathbf{A}$, given by $\mathbf{A} = A(\rho, z) \hat{\varphi}$ in cylindrical coordinates (ρ, φ, z) . Finding the curl of the potential and assuming that we are just outside the sheet in a current-free region gives Laplace's equation, which can be solved to find an expression for the potential. From this the current sheet magnetic field can be calculated, given by

$$B_\rho = \begin{cases} \text{sign}(z) \mu_0 I_0 \int_0^\infty J_1(\lambda \rho) J_0(\lambda R_1) \sinh(\lambda D) e^{-\lambda |z|} \frac{d\lambda}{\lambda}, & \text{for } |z| > D \\ \mu_0 I_0 \int_0^\infty J_1(\lambda \rho) J_0(\lambda R_1) \sinh(\lambda z) e^{-\lambda D} \frac{d\lambda}{\lambda}, & \text{for } |z| \leq D, \end{cases} \quad (2.6)$$

$$B_z = \begin{cases} \mu_0 I_0 \int_0^\infty J_0(\lambda \rho) J_0(\lambda R_1) \sinh(\lambda D) e^{-\lambda |z|} \frac{d\lambda}{\lambda}, & \text{for } |z| > D \\ \mu_0 I_0 \int_0^\infty J_0(\lambda \rho) J_0(\lambda R_1) [1 - e^{-\lambda D} \cosh(\lambda z)] \frac{d\lambda}{\lambda}, & \text{for } |z| \leq D, \end{cases} \quad (2.7)$$

where $J_n(x)$ is a Bessel function of the first kind for integer n . Note that these equations are for a current disc that stretches to infinity. For a finite current disc, we create a superposition of two current sheets, one of which approaches infinity from R_1 , and the other approaches negative infinity from R_2 , which becomes the outer edge of the current sheet. The presence of the current sheet distorts the ambient planetary magnetic field from being dipolar to disc-like, as is observed in Figure 2.8.

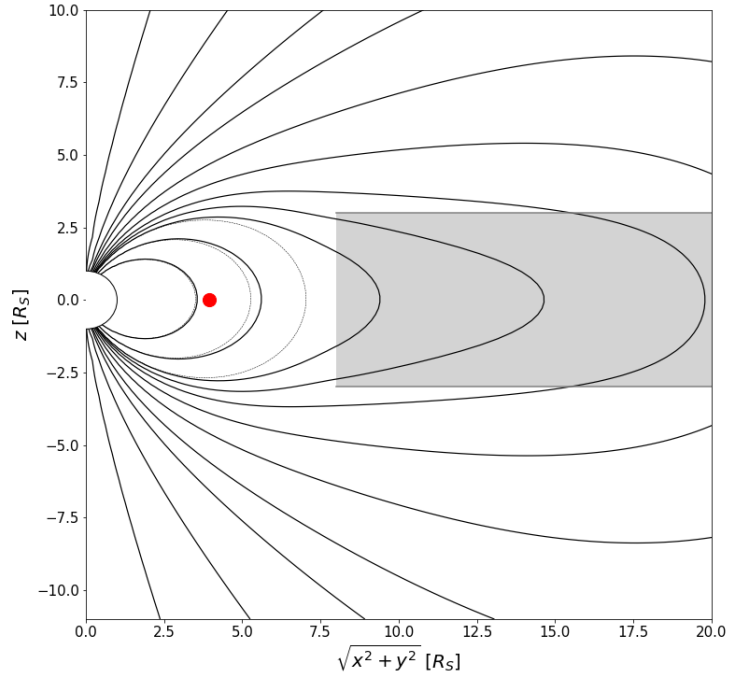


Figure 2.8: Plotted in a cylindrical $\rho-z$ plane the magnetodisc current sheet is shown in grey, with the associated radially stretched magnetic field lines in black and the unperturbed dipole field lines in light grey. The red dot indicates Enceladus.

2.3.3 Plasma Distribution and Flow

The primary source of plasma to the Saturnian magnetosphere is Enceladus. It produces neutral water group molecules that become ionised through photoionisation, impact ionisation and charge exchange [Bagenal and Delamere, 2011]. The rings are another source of water group ions due to ionisation of its ice grains, but to a lesser extent compared to Enceladus [Dougherty et al., 2009]. Plasma is transported outwards from the inner magnetosphere before inevitably being lost from the system. An unex-

pected feature observed is the non-adiabatic increasing temperature with radial distance of heavy ions sourced from Enceladus [e.g. Thomsen et al., 2010, Wilson et al., 2017]. A similar phenomena occurs at Jupiter with relation to its heavy ion population sourced by the volcanic moon Io [e.g. Bagenal and Delamere, 2011]. It has been suggested that oppositely directed Alfvén waves, driven by both large-scale and small-scale stresses acting on the system, interact non-linearly and trigger a turbulent cascade. In the middle to outer magnetosphere, the first kinetic scale this energy cascade would interact with is the heavy ion gyroperiod and thus energy will be deposited resulting in this increasing temperature profile [Saur, 2004, Saur et al., 2018]. A similar mechanism has been attributed to the feature seen at Saturn for the water group ions [von Papen et al., 2014].

In the inner magnetosphere ($< 15 R_S$) a noon-midnight electric field has been observed of yet unknown origin (see review by Thomsen et al. [2012] and references therein). The associated convection pattern with this electric field is fixed in local time such that particles drift radially outwards at dawn and radially inwards at dusk. These drifts have been measured directly using the CAPS Ion Mass Spectrometer (IMS) data (see Section 3.2.2 for instrument description) [Wilson et al., 2013]. The drift pattern would result in adiabatic heating of the plasma on the nightside and cooling on the dayside. A day-night asymmetry in the plasma temperatures consistent with this has been observed. The temperature of the water group ions sourced from Enceladus are hotter on the nightside compared to the dayside at radial distances less than $15 R_S$ [Wilson et al., 2017]. This convection electric field appears to explain several asymmetries in the magnetosphere of Saturn [Thomsen et al., 2012].

The measured distribution when calculating moments from the counts (see method in Chapter 3.2.2) is often not best described by a Maxwellian, with prominent tails revealing a high-energy population. The suprathermal plasma ($> \text{keV}$) is found to predominantly reside in the middle to outer

magnetosphere and is not centrifugally confined to the equator like the heavy ions. Following nightside reconnection in the tail, the return flow plasma is accelerated as the tension in the stretched field causes it to dipolarise and moves planetwards, resulting in hotter populations $\sim$ keV [Badman and Cowley, 2007]. Energetic particles can also be found in the inner magnetosphere follow interchange with the heavy Enceladus plasma, as discussed in Section 2.3.2. The relative abundance of thermal and suprathermal plasma can be measured by comparing their contribution to the total plasma pressure. The suprathermal plasma dominates at distances close to $9 R_S$ but exhibits minor local time dependence, dominating at smaller radial distances at night and dusk [Sergis et al., 2017]. The total plasma beta typically exceeds unity past $9 R_S$ [Bagenal and Delamere, 2011] revealing the large-scale structure of the magnetosphere will likely be shaped and dragged by the plasma in these regions.

2.3.4 Planetary Period Oscillations

Before the arrival of the Cassini spacecraft, analysis by Espinosa and Dougherty [2000] using data from Pioneer 11, Voyager 1 and 2 identified periodic perturbations in the magnetic field that were puzzling. One would assume this is due to a tilt between the dipole and spin axes, but at Saturn there is almost no tilt [Dougherty et al., 2018]. The modulations appeared to be well described by sinusoids with a period of the assumed rotation rate of Saturn, calculated from measurements of SKR [Kaiser et al., 1980, Desch and Kaiser, 1981]. Once Cassini arrived at Saturn Cowley et al. [2006] confirmed that these signatures were still present. Modulations at the approximate rate of the planetary rotation period, known as planetary period oscillations (PPOs), have since been observed in almost all the Cassini datasets, including the plasma and energetic particle data and observations of auroral UV emissions (see review by Carbary and Mitchell [2013] and references therein).

The magnetic field signatures can be described by two rotating current systems. Each hemispheric current system consists of field-aligned currents that flow into the ionosphere, across the polar region as Pederson currents, out of the ionosphere and close either in the equatorial current sheet or in the other hemisphere [e.g. Hunt et al., 2015]. The closure of these currents in the ionosphere is shown in Panel's a) and d) of Figure 2.9. By Equation 1.4 these currents will produce a magnetic field and its configuration is shown in Figure 2.9. The perturbation magnetic field is quasi-uniform in the equatorial region and quasi-dipolar (transverse to the planetary dipole) in the polar regions. The separate PPO systems are identified with a phase angle $\Psi_{N,S}$ that defines the azimuth of the PPO systems such that $\Psi_{N,S} = 0^\circ$ when the field perturbation points radially outwards and $\Psi_{N,S} = 180^\circ$ when the field perturbation points radially inwards, as shown in Panels b) and e) of Figure 2.9. Since the PPO systems rotate, at a fixed spatial location the phase angle increases at the rate of the given PPO period. A leading theory for the physical origin of these PPOs comes from MHD simulations that have shown twin rotating vortices in the polar regions of Saturn's thermosphere can drive perturbations upwards into the magnetic field, generating hemispheric field-aligned current systems that rotate with the planet and produce this effect [Smith, 2006, Jia et al., 2012]. However, the assumed ionosphere vortical flow patterns in the simulations have yet to be observed.

The phases and periods of the PPOs have been determined using magnetic field and SKR data for the complete Cassini mission. Each hemispheric system appears to rotate with different and varying periods, close to ~ 10.6 hours [Hunt et al., 2014, 2015, 2016, Southwood and Kivelson, 2007, Southwood and Cowley, 2014] and vary with season [Andrews et al., 2008, 2012, Cowley and Provan, 2015, 2016, Gurnett et al., 2009, Gurnett et al., 2011, Kurth et al., 2007, 2008, Lamy, 2011, 2017, Provan et al., 2013, 2014, 2016, 2019b]. The phases identified will be used in Chapter 5 and so

we will briefly explain how they are derived. Initially, the northern and southern phases were identified in the SKR data [Kurth et al., 2008, Gurnett et al., 2009]. These emissions are due to the cyclotron maser instability linked to downward (with respect to the ionosphere) accelerated auroral electrons and upward PPO currents [Lamy, 2011]. The phases are also calculated directly from the magnetic field data and both datasets in general show good agreement [e.g. Provan et al., 2019b]. To determine the phases, an internal field model is subtracted from the data before it is band-passed filtered between 5 and 20 hours to isolate perturbations in the band close to the planetary period. A rotating sinusoidal function is fitted, using a least-squares method, to the filtered spherical magnetic field components during quiet intervals, given by

$$B_i(\phi, t) = B_{0i} \cos(\Phi_g(t) - \phi - \psi_i) \quad (2.8)$$

for $i = r, \theta, \phi$ where the PPO perturbation field strength B_{0i} and phase ψ_i is determined by the fit. The relative phases in θ and ϕ are assumed to be in phase with r that are described by the sketch in Figure 2.9. For instance, θ is in phase or in anti phase with r for southern or northern PPO data, respectively. The other parameters are $\Phi_g(t)$, a chosen guide phase that has a period close to the period of the data oscillations, and ϕ , the azimuth angle measured as zero at noon that increases in the direction of rotation. The separate northern and southern phases can be identified when Cassini is sampling each hemisphere, whilst at the equator both systems dual-modulate the field. Due to variability in the data, phases cannot always be identified, and so linear fits between revolutions (revs) that are average over ~ 200 days are used to define $\Psi_{N,S}(t)$ for the entire Cassini mission. The northern and southern PPO phases are then given by $\Phi_{N,S}(t) = \Phi_g(t) - \psi_{N,S}(t)$ and these describe the phase angle from noon to where the equatorial PPO field points radially outwards. Finally, the phase function that describes the azimuth angle with respect to the northern and

southern PPO systems is given by

$$\Psi_{N,S} = \Phi_{N,S} - \phi \quad (2.9)$$

where $\Psi_{N,S} = 0^\circ$ when the equatorial PPO field points radially outwards. This describes the local phase of each system seen by an observer. These phase angles are shown in Figure 2.9 and will be used to compare the PPOs to properties of the magnetodisc current sheet in Chapter 5.

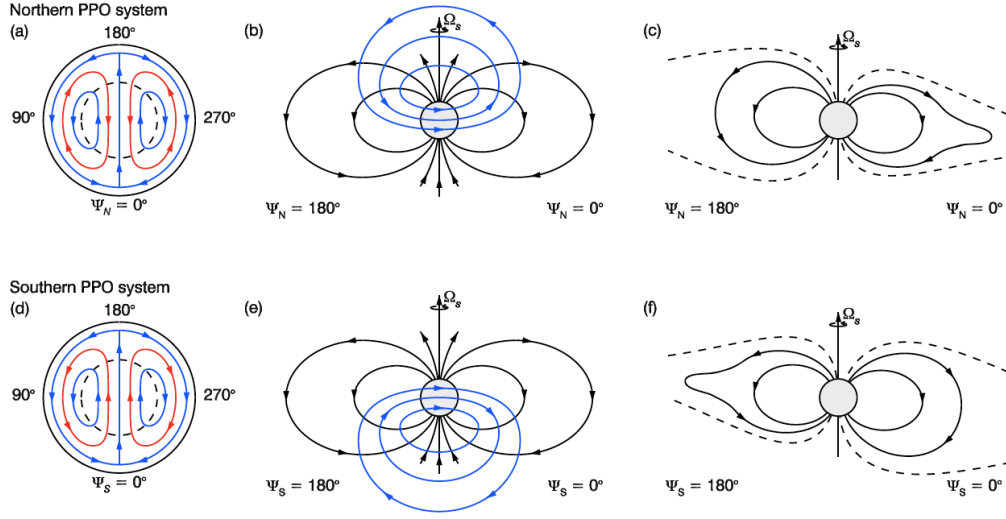


Figure 2.9: Sketches of the PPOs, with the top panels the northern system and the bottom panels the southern system. Panel's a) and d) look down onto the ionosphere (through the planet for Panel d)) with the red lines showing the ionospheric flow and the blue lines the PPO magnetic perturbation fields. Panels b) and e) show the two perturbation systems in the meridional plane on top of a background magnetodisc field. Panel's c) and f) show the PPO modulations of the field as described in text. Sketch taken from Bradley et al. [2018].

These rotating perturbation systems modify the large-scale structure of the magnetodisc current sheet, as is shown in Figure 2.9. Both systems are present at the equator where they constructively and destructively interfere. Firstly, the PPOs produce north-south modulations of the current

sheet location. As shown in Panel's b) and e) of Figure 2.9, when $\Psi_{N,S} = 0^\circ$ the current sheet is displaced south of the magnetic equator due to pressure balance, since the quasi-uniform field points radially outwards and adds to the background field above the equator and subtracts from it below the equator. The sheet is displaced northwards when $\Psi_{N,S} = 180^\circ$ due to the vector addition of the fields being in the opposite sense. This results in a periodic flapping of the current sheet as the current systems rotate. Secondly, the colatitudinal component of PPO fields produces thickness modulations of the current sheet. If the PPO fields points southward (northwards), then it adds (subtracts) to the background field, resulting in a thickening (thinning) of the current sheet. The thickness modulations by each PPO system cancel when they are in phase, with the displacement being enhanced, whereas when they are in anti-phase the thickness modulations are enhanced and the displacement cancels out.

Variations in the thickness and offset of the current sheet have been observed in the tail current sheet, where the thickness varies by a factor of ~ 2 with an offset amplitude of $\sim 3 R_S$ [Provan et al., 2012]. The thickness modulation can be identified by a sawtooth signature in the radial component if Cassini remains near the equator [Thomsen et al., 2017, Cowley and Provan, 2017]. These modulations were subsequently modelled [Aurridge et al., 2011, Cowley et al., 2017] using a simple sinusoidal functional form that depends on the nominal current sheet thickness, offset due to the seasonal warping of the sheet and relative strengths of the PPO current systems. This model was found to well describe the highly-variable B_r profiles during the F-ring orbits [Agiwal et al., 2020], showing the importance of PPO modulations for dynamics and structure. Bradley et al. [2018] further found that plasmoid releases in the magnetotail occur favourably at phases of the northern and southern PPOs when the current sheet is being thinned ($\Psi_N = 0^\circ$ and/or $\Psi_S = 180^\circ$). The dynamics of the Saturnian system appear to be controlled by a combination of the externally-driven

Dungey-cycle, internally-driven Vasyliūnas cycle and the PPOs.

2.3.5 The Magnetopause

The magnetopause is the pressure balance boundary between the magnetic field of a magnetized body and the IMF. At Earth, the planetary magnetic field is the dominant contributor to the pressure balance, as assumed for the calculation of Equation 1.19. At Saturn, pressure associated with energetic particles is of the same magnitude as the magnetic pressure and can therefore modify the location of the magnetopause. Pilkington et al. [2015a] found that the magnetopause standoff distance exhibits a bimodal distribution, with peaks at 21 and 27 R_S . Whilst a range of dynamic pressures associated with the solar wind are expected, they do not have a bimodal distribution [Achilleos et al., 2008] and can instead be described by a single peak [Jackman and Arridge, 2011a, Jackman et al., 2019], and is thus unable to explain the additional peak. Instead, the second peak could be due to internal sources, with variable outgassing of Enceladus [Smith et al., 2010] and mass loss via Vasyliūnas reconnection in the tail resulting in the system varying between being mass-loaded and mass-depleted. When the magnetosphere is in a plasma-loaded regime, with a standoff distance of greater than 24-25 R_S the magnetosphere becomes more compressible [Sorba et al., 2017, Hardy et al., 2020]. This highlights how the Saturnian magnetopause acts similar to both Jupiter and Earth - the boundary behaviour switches from being more compressible (like Jupiter) or more stiff (like Earth) depending on the internal mass content and system size.

Pilkington et al. [2015b] updated their magnetopause model to incorporate a dawn-dusk asymmetry that improved the model fit to the data. They suggest this could arise due to the asymmetry in internal plasma flow with respect to the solar wind. At dusk, the two flows are parallel such that the force balance moves towards Saturn, whilst at dawn they are antiparallel, allowing the internal plasma to push back against the solar wind and mov-

ing the magnetopause outwards. Pilkington et al. [2015b] found that the magnetopause is 7% farther out at dawn compared to dusk, whilst MHD simulations found a slightly larger difference [Kivelson and Jia, 2014], as shown in Figure 2.10. This could be due to the simulation not including suprathermal plasma and thus any asymmetries in the associated pressure at dawn and dusk [Sorba et al., 2019].

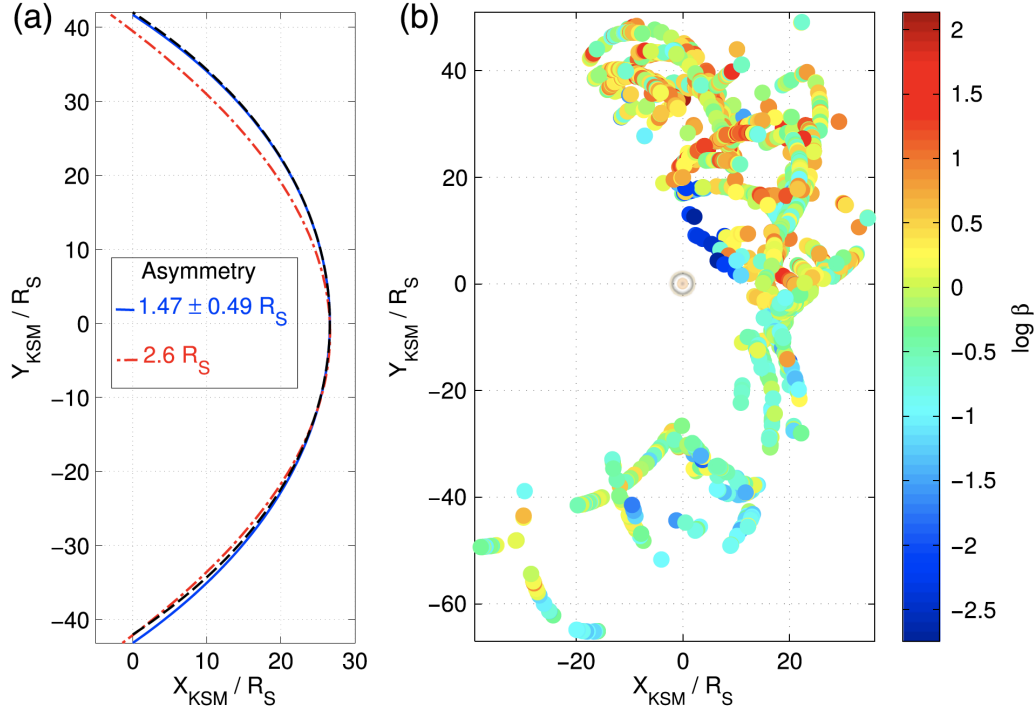


Figure 2.10: The asymmetric magnetopause model of Pilkington et al. [2015b] compared with the Kivelson and Jia [2014] MHD model, alongside measured β values during magnetopause crossings. Figure from Pilkington et al. [2015b].

The magnetopause boundary can be described with the asymmetric empirical model of Pilkington et al. [2015b], given by

$$\begin{aligned}
r &= R_{SS} \left(\frac{2}{1 + \cos \theta} \right)^K \\
R_{SS} &= a_1 D_p^{-a_2} \\
K &= a_3 + a_4 D_p + a_5 \cos \phi,
\end{aligned} \tag{2.10}$$

where (r, θ) are the polar coordinates of a point on the magnetopause, K is the flaring parameter that describes the magnetopause shape downstream, $\phi = \cos^{-1}(Y_{KSM}/r \sin \theta)$ (see Section 3.3 for KSM coordinates description) such that $\cos \phi$ increases the flaring on one side of the magnetopause and decreases on the other, and a_{1-5} are the fitted coefficients describing various states of the magnetopause and its response to the solar wind, given as $a_1 = 10.5 \pm 0.2$, $1/a_2 = 5.7 \pm 0.1$, $a_3 = 0.67 \pm 0.01$, $a_4 = 0.17 \pm 0.03$ and $a_5 = -0.03 \pm 0.01$ [Pilkington et al., 2015b]. This model can map the nose standoff distance from a crossing of the magnetopause at any location.

2.4 Summary

In this chapter the Saturnian magnetosphere and its key features were introduced. The landmark discovery of Enceladus being a plasma source [Dougherty et al., 2006] shapes our understanding of the large-scale structure of the Saturnian magnetosphere. This thesis will study the large-scale structure of the current sheet that is populated by Enceladus-sourced plasma. To analyse the structure, an understanding of what could be potential sources of variability is required. This chapter has introduced the key topics required for the upcoming work chapters.

The first work chapter will discuss changes in magnetodisc parameters with system size. We have therefore introduced previous modelling efforts of the current sheet [e.g. Bunce et al., 2007, Achilleos et al., 2010] and a discussion of the magnetopause properties. The second chapter will explore

current sheet thickness and so we have introduced topics regarding plasma distribution and flow [e.g. Sergis et al., 2011, Bagenal and Delamere, 2011] and sources of temporal variability, such as the PPOs. The final chapter will study the cushion region of Saturn and the structure of the outer magnetosphere. The introduction of plasma processes near the boundary and magnetodisc formation and breakdown provide the foundation for this study.

Hence, this review chapter provides the motivation for the following chapters that will explore how the large-scale structure of the current sheet responds to these different factors.

Chapter 3

The Cassini-Huygens mission

Before the Cassini-Huygens mission, Saturn had only been visited by flybys of spacecraft. In 1979, Pioneer 11 made an equatorial pass of Saturn, reaching as close as $1.35 R_S$ that revealed a small tilt, albeit with large error bars, between the magnetic field and rotational axes [Smith et al., 1980, Smith et al., 1980]. The Voyager 1 flyby in 1980 and Voyager 2 flyby in 1981 had greater latitudinal coverage ($\pm 30^\circ$) and further measured the axisymmetry whilst also determining the variability of external magnetic field contributions, such as the magnetodisc current sheet [Ness et al., 1981, 1982, Connerney et al., 1981b, Connerney et al., 1982, Connerney et al., 1983].

However, many features of the magnetic field of Saturn were still not understood. An orbital mission was required for a comprehensive survey of the large-scale structure and dynamics. In this chapter we will discuss the Cassini mission and the necessary instrumentation required for the research presented in this thesis. The content discussed in this chapter will mainly come from the book [Dougherty et al., 2009] unless otherwise referenced. The reader may also want to refer to other key review papers of Cassini [e.g. Dougherty and Spilker, 2018, Spilker, 2019].

3.1 The Mission



Figure 3.1: Photograph of the Cassini-Huygens spacecraft during testing. Image from NASA.

The Cassini-Huygens spacecraft, pictured in Figure 3.1, was a flagship-class mission of NASA/ESA/ASI that launched in October 1997 from Cape Canaveral Air Force Station in Florida, USA. The mission objectives whilst exploring Saturn included a determination of the atmosphere and composition of its moons, understanding the dynamics of the planetary rings and characterising the key features of its magnetosphere [Dougherty et al., 2009].

The Cassini spacecraft was over six metres tall and four metres wide (see Figure 3.1). It was powered by Radioisotope Thermoelectric Generators (RTGs) due to the distance from the Sun making the required solar

panels too large for the spacecraft, and had 12 instruments onboard to measure the different phenomena in the near-space environment of Saturn.

Following the successful launch of the mission in 1997, the mission entered the cruise phase which included swing-bys of Earth, Venus and Jupiter as gravitational assists to reach Saturn. The trajectory of Cassini through interplanetary space from the Earth to Saturn is shown in Figure 3.2.

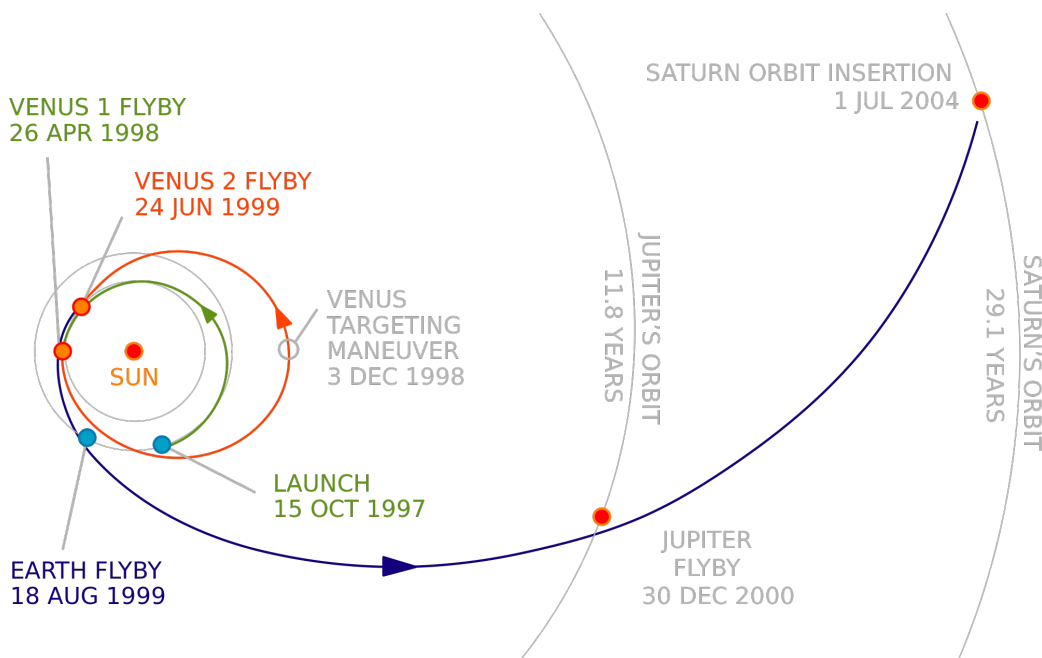


Figure 3.2: Graphic showing Cassini's trajectory from Earth to Saturn. Credit: NASA / Jet Propulsion Laboratory.

In June 2004, Cassini fired its main engine to slow down and be captured at Saturn, known as orbital insertion, with periapse at $1.33 R_S$. The Huygens probe detached and landed on Titan in late-2004. The Cassini spacecraft then orbited Saturn for 14 years, having initially only been planned for 4 years. Throughout the mission, the spacecraft manoeuvred between equatorial and high-latitude orbits, exploring different magnetic and plasma environments across the entire mission, allowing for a greater mapping of

the environment. The mission ended with a set of orbits that went closer to the planet than ever before, diving between the rings and the cloud tops. The spacecraft plummeted into the atmosphere of Saturn on September 15th 2017.

The complete orbital trajectory of Cassini at Saturn is shown in Figure 3.3, revealing the different phases of the mission. For the early phase of the mission, Cassini remained near the equator but explored large radial distances from the planet. In 2008, the mission was given a two-year funding extension, having only intended to last for four years. This phase, known as Cassini Equinox Mission, allowed for an exploration of the high-latitude regions. The mission was then given a longer extension until 2017, which included multiple flybys of the moons Titan and Enceladus. The final phase of the mission included the F-ring orbits and the Grand Finale orbits where Cassini went closer to Saturn than a spacecraft had ever been.

For the first work chapter where we quantify a global stress index for Saturn, we will use Cassini measurements made at small radial distances, low latitudes, and in all local time sectors excluding near midnight. For the second work chapter where we study the thickness of the current sheet, we will use data from a larger range of radial distances, during steep crossings of the equatorial region and in all local times. Finally, for the third work chapter where we analyse the cushion region at Saturn, our work will use data at larger radial distances, at lower latitudes close to the equator and on the dayside. Therefore, the work presented in this thesis covers a wide range of regions in the Saturnian system that will survey almost all of the Cassini data.

3.2 Instrumentation

The research presented in this thesis relies on data collected by the Cassini spacecraft. Primarily, this work will analyse the magnetic field data col-

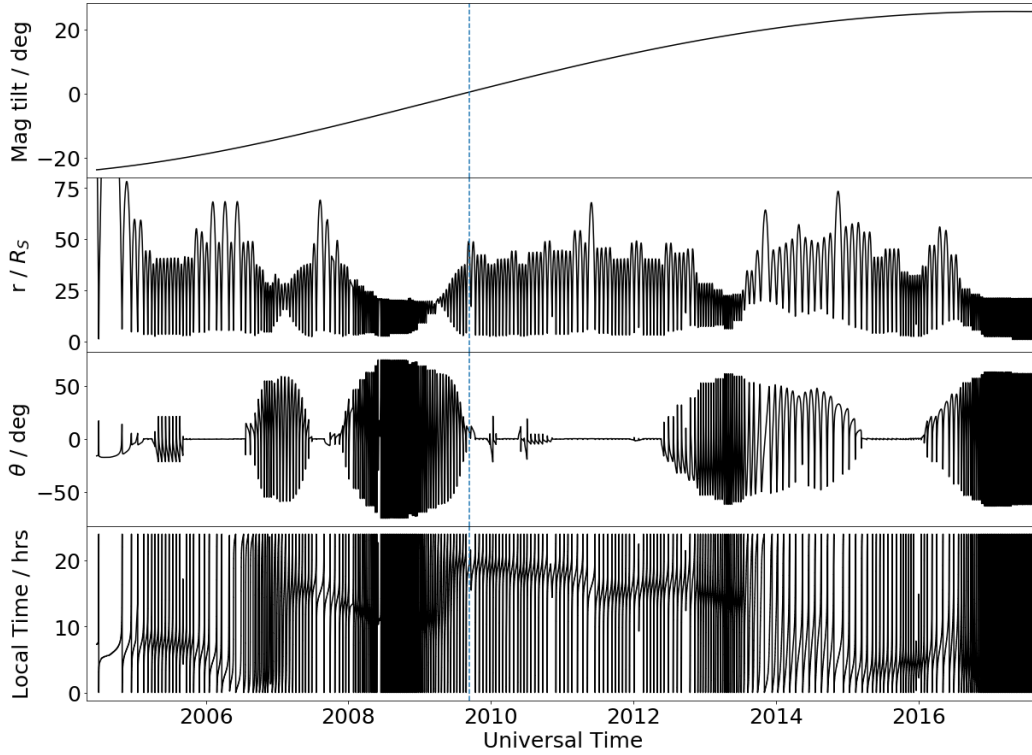


Figure 3.3: The complete Cassini orbital mission trajectory is shown. The top panel showing the magnetospheric tilt of the planet with respect to the Sun. The second panel shows the radial distance of Cassini from Saturn. The third panel shows Cassini’s latitude. The fourth panel shows Cassini’s azimuthal location in terms of local time. The blue dashed line shows equinox in August 2009.

lected by the Fluxgate Magnetometer to study the large-scale structure of the Saturnian magnetosphere. Data from the Cassini Plasma Spectrometer will also be used for supporting analysis to compare the local plasma environment to the magnetic field measurements. All data used in this thesis is available at the Planetary Plasma Interaction (PPI) Node of NASA’s Planetary Data System (PDS).

3.2.1 Fluxgate Magnetometer

The Cassini mission had two instruments onboard for magnetic field measurements - the Vector/Scalar Helium Magnetometer (V/SHM), built at the NASA Jet Propulsion Lab, and the Fluxgate Magnetometer (FGM), built at Imperial College London [Dougherty et al., 2004]. Both of these were attached to an 11-metre non-metallic boom with the V/SHM being placed at the end of the boom, and the FGM halfway along. The boom is to ensure that neither instrument measures external magnetic fields due to, for instance, the spacecraft which can become charged in ionised environments, or fields due to other instruments onboard the spacecraft. The distance between each instrument allows for a better determination of spacecraft generated fields. The spacing also provides calibration capabilities between the instruments for calculating their zero levels, which can change after launch not only due to spacecraft charging but for instance due to changes in temperature and instrument ageing [Kellock et al., 1996].

Two years after launch, the boom was deployed and the magnetometers were switched on. The initial Earth swing-by allowed for a calibration of both magnetometers and provided some new science opportunities, with the V/SHM instrument identifying a magnetic storm [Smith et al., 2001]. Benefits of a dual magnetometer set-up include reliability of in-flight calibration, better determination of the spacecraft field and redundancy [Kellock et al., 1996]. Unfortunately, the V/SHM failed within a year of Cassini arriving at Saturn. Hence, the research presented in this thesis will utilise the FGM dataset.

The FGM, shown in Figure 3.4, measures the magnetic field strength and direction via three perpendicular core sensors mounted on a ceramic block. This material is chosen due to its low thermal expansion coefficient, preventing misalignments with changing temperature. The ring core is a highly permeable metal that is wound by a toroidal drive winding and encased by a rectangular sense winding. This set up is shown in Figure 3.5.

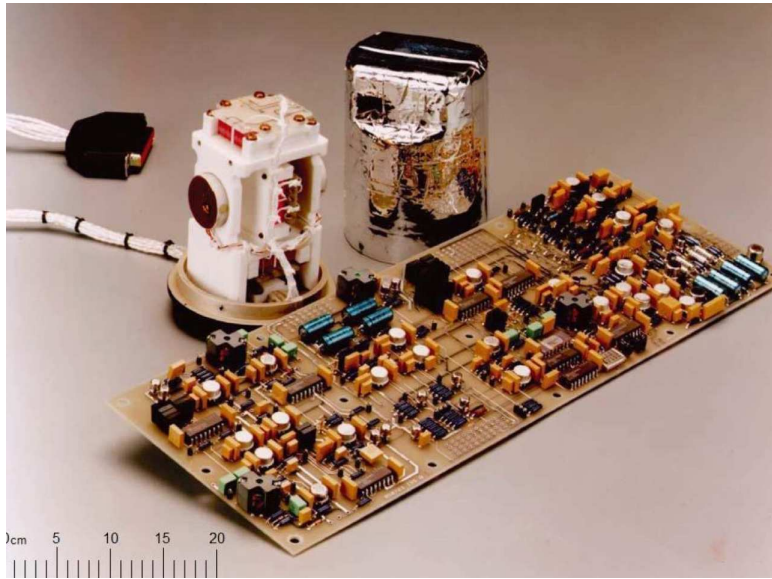


Figure 3.4: The Cassini Fluxgate Magnetometer (FGM), showing the sensor, the sensor case and electronics board to be placed on the spacecraft. Image taken from Dougherty et al. [2004].

A bipolar current is driven through the drive winding coil at a frequency of 15.625 kHz. This forces the core in and out of saturation. If there is no external field the two halves of the core will go in and out of saturation symmetrically and there is no change of flux in the sense winding. However, if there is an external field one half of the core will become saturated before the other and the fields generated will not cancel out. By Equation 1.3 this non-zero flux will induce a voltage in the sense winding that is proportional to the external magnetic field component parallel to the axis of the core. The three-dimensional external magnetic field measurement is determined using all three orthogonal sensors [Dougherty et al., 2004].

The FGM has a cadence of 32 vectors per second and works in four operating ranges: ± 40 nT, ± 400 nT, $\pm 10,000$ nT and $\pm 44,000$ nT per axis, with a corresponding resolution of 4.9 pT, 48.8 pT, 1.2 nT and 5.4 nT. The instrument automatically switches between these ranges depending on the

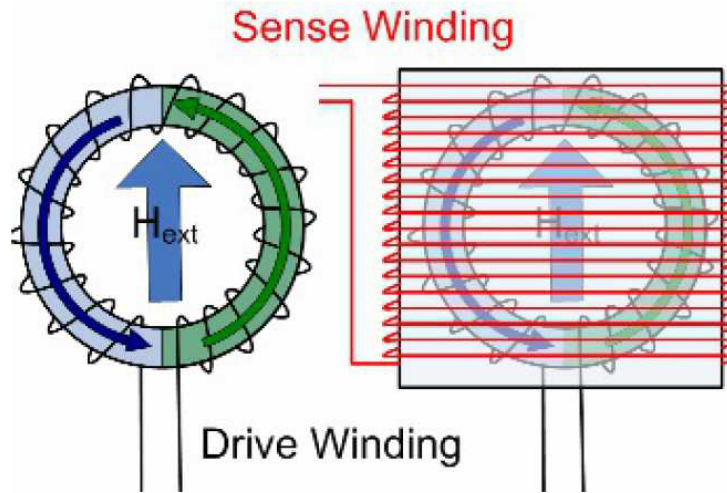


Figure 3.5: Single axis of the fluxgate magnetometer. The core and drive winding are shown in the left image and will measure the external magnetic field in the direction of H_{ext} . The right image shows the sense winding that encases the core and drive winding. When $H_{ext} = 0$ the two halves (green and blue) of the ring will go in and out of saturation at the same time. However, when $H_{ext} \neq 0$ the blue half will come out of saturation sooner and the green half later. This non-zero flux will induce a voltage in the sense winding. Image credit: Imperial College London.

measured local environment, with the aim for the largest range to only be used for ground testing and the Earth flyby [Balogh, 2010].

The magnetometer was initially calibrated in a controlled laboratory environment. However, once Cassini launched, in-flight calibration was undertaken in a changing and more challenging environment. The Earth swing-by was used for calibration as the magnetometer data could be compared to the Earth's magnetic field. In the interplanetary magnetic field and at Saturn, rolls of the spacecraft were used for calibration which separate the rotating external magnetic field from the static spacecraft field and sensor offsets [Dougherty et al., 2004]. These manoeuvres were beneficial since they allowed for a calibration of the FGM once the V/SHM had failed.

For the Grand Finale orbits, shown in Figure 3.6, the spacecraft had to prepare for an unplanned portion of the mission which it had not been calibrated for. The close proximity of the Grand Finale orbits to Saturn had never been previously explored, a region where the magnetic field strength is large enough (peak measurement of $\sim 18,000$ nT) to require the highest measurement range mode for the FGM that had not been used for 18 years since the Earth flyby. The spacecraft performed rolls at periapse during multiple Grand Finale orbits to calibrate the instrument, ready for these observations [Dougherty et al., 2018].

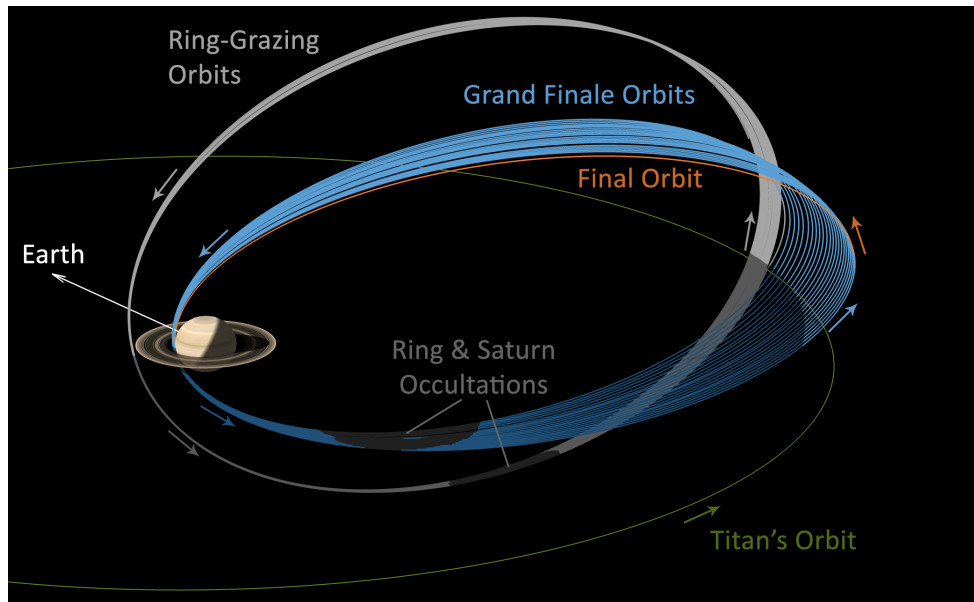


Figure 3.6: The ring-grazing and grand finale orbits of the Cassini mission. Image from NASA.

3.2.2 Cassini Plasma Spectrometer

The Cassini Plasma Spectrometer (CAPS) suite [Young et al., 2004], shown in Figure 3.7, contained three sensors that measured electrons and ions in energy ranges of ~ 0.1 to $\sim 10,000$ eV. Unfortunately, these sensors were

turned off in 2012 due to suffering a series of short circuits, but data up until then can be used for analysis.

Since Cassini was a three-axis stabilised spacecraft and plasma measurements typically want a spinning spacecraft, the CAPS instrument was mounted on a rotating actuator platform, providing a total field of view that covers close to 2π steradians every three minutes, allowing the instrument to face incoming plasma and provide the azimuthal angle of arrival.

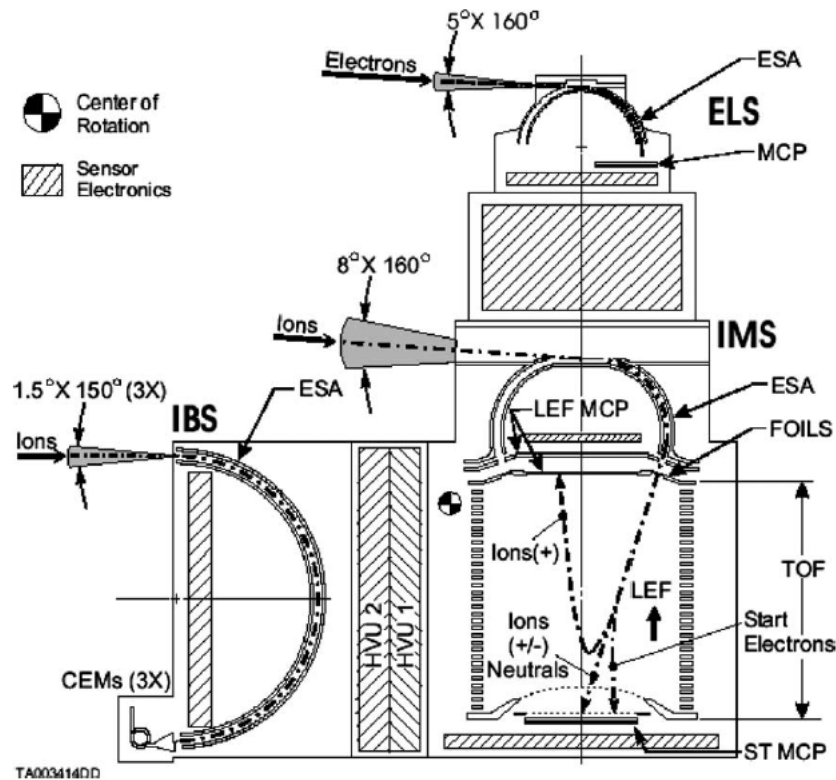


Figure 3.7: The CAPS suite of plasma instruments, shown in $x - y$ plane with particle trajectories shown as dashed lines. Image taken from Young et al. [2004].

Electrons

The Electron Spectrometer (ELS) measures electron distributions between ~ 0.5 eV to ~ 25 keV. The instrument is a top-hat electrostatic analyser (ESA, see Figure 3.7) that uses electric fields to deflect electron trajectories of a given energy-per-charge ratio. Once electrons enter the 5° aperture, there are two plates that are charged through 63 discrete voltage steps for 31.25ms per step. This electric field will deflect the particle trajectory, based on Equation 1.5, for electrons in each given E/q ratio (63-level logarithmic energy spectrum), allowing them to enter the chamber and be measured by a Micro-Channel Plate (MCP) detector. Eight anodes behind the detector with a field of view of $5^\circ \times 20^\circ$ can identify the elevation angle of arrival depending on which anode detects the electron. Anode 5 is commonly used due to its field-of-view not being obscured by other Cassini instruments. From knowing the counts per energy range and the two angles of arrival, velocity distributions can be calculated.

The ELS instrument energy range provides the opportunity to measure many different environments in the magnetosphere of Saturn. The lower range is ideal for the inner magnetospheric region, compared to the higher range which is used to measure the higher energy, hotter regime in the outer magnetosphere.

The moments calculated by Lewis et al. [2008] will be used in Chapter 5 to determine the properties of the plasma sheet for comparison with the current sheet identified using magnetometer data. To calculate the moments, Lewis et al. [2008] firstly remove the spacecraft potential to correct the counts determined by the ELS. The bulk parameters can then be calculated using either the 3D method involving integrating a distribution function about a volume of velocity space, or the 1D method that fits a Maxwellian to the energy distribution, where the temperature is the peak of the distribution and the density is the area. The latter method provides a quick and easy way to calculate the moments, at the expense of precision

by underestimating, as it only accounts for part of the distribution that is fitted with the Maxwellian (unless multiple curves are fit). It should be noted that both methods assume an isotropic distribution of electrons. The work in Chapter 5 will use the moments calculated using the 3D method.

Ions

The Ion Mass Spectrometer (IMS) uses an ESA with a time of flight method, measuring the time between a start and stop signal, to determine the velocity, species and counts of ions species with energies from ~ 1 eV to ~ 50 keV. Moments calculated from the IMS by Wilson et al. [2017] are used in Chapter 6. To calculate the moments from the IMS counts Wilson et al. [2017] used a 3D forward model fitting approach which provides the benefit of identifying anisotropies. By assuming a Maxwellian distribution for the ion species, one can define the counts expected from given density, temperature and velocity values. This can then be compared with the counts measured by IMS until best agreement between the data and expected model values is achieved. Using this method does not account for high-energy ions that will appear as a tail in the distribution, but can be used to identify two ion species (H^+ and W^+). Since the spacecraft is not spinning, even though the actuator provides a wider field of view the volume of velocity space is nonetheless inhibited. This means that the ion distribution peak might not be observed by the sensor. The moments are more easily calculated for the electrons, hence why the ELS data is often used.

3.2.3 Other Fields and Particles Instruments

As well as MAG and CAPS, there were other instruments onboard Cassini for measuring the electromagnetic fields, charged and neutral particles in the Saturn system. These instruments will be briefly introduced and refer-

ences will be provided, but they will not be discussed as their datasets were not used in this thesis.

The Magnetosphere Imaging Instrument (MIMI) was built for taking images of Saturn and taking in-situ particle measurements using its three sensors - the Ion and Neutral Camera (INCA) for energetic neutrals and ions, the Low Energy Magnetospheric Measurements System (LEMMS) for charged particles, and the Charge-Energy-Mass-Spectrometer (CHEMS) for ion energy, mass, charge and 3D anisotropy [Krimigis et al., 2004]. In addition, the Radio and Plasma Wave Science (RPWS) suite on Cassini was composed of seven sensors that were used to study radio emissions, plasma waves and dust at Saturn. This suite included three orthogonal electric field antennas, three orthogonal magnetic field search coils and a Langmuir probe to measure electron density and temperature [Gurnett et al., 2004]. The Ion and Neutral Mass Spectrometer (INMS) was used for determining neutral particle composition which was essential for studying Titan's upper atmosphere [Waite et al., 2004]. Finally, the Cosmic Dust Analyzer (CDA) was developed to study interplanetary dust near Saturn and study the composition of Saturn's rings [Srama et al., 2004].

Hence, this suite of instruments allowed for a complete exploration of the fields and particles in the near-space environment of Saturn.

3.3 Coordinate Systems

The Kronocentric Solar Magnetospheric (KSM) cartesian coordinates are commonly used for Cassini data. In this frame, the unit vector $\hat{x}$ points towards the Sun, $\hat{M} \times \hat{x} = \hat{y}$ where $\hat{M}$ is the unit vector aligned with the dipole of Saturn, and $\hat{z}$ completes the right-handed set and is set in the plane containing $\hat{M}$ and the unit vector pointing towards the Sun.

We will work primarily in the Kronocentric Solar Magnetic (KSMAG) system, shown in Figure 3.8, which instead aligns the coordinates with the

dipole axis of Saturn. To do this, the KSM coordinate system is rotated around $\hat{y}$ by the solar latitude, given by

$$\begin{aligned}x_{KSMAG} &= x_{KSM} \cos(\theta_S) + z_{KSM} \sin(\theta_S) \\y_{KSMAG} &= y_{KSM} \\z_{KSMAG} &= -x_{KSM} \sin(\theta_S) + z_{KSM} \cos(\theta_S),\end{aligned}\tag{3.1}$$

where

$$\begin{aligned}\theta_S &= -1.371^\circ - 25.69^\circ \cos(2.816 + 0.213499t_{YR}) \\&\quad + 1.389^\circ \cos(5.4786 + 0.426998t_{YR}),\end{aligned}\tag{3.2}$$

is the latitude of the Sun with respect to Saturn and t_{YR} is the fractional year [Arridge et al., 2008a]. This coordinate transformation is shown in Figure 3.8. The coordinates are now based on the dipole axis of Saturn, which is close to identical to the rotation axis of Saturn [Dougherty et al., 2018]. In spherical KSMAG coordinates, r is the radial component and positive pointing away from Saturn, θ is the latitudinal component and ϕ is the azimuthal component increasing in the direction of rotation and 0° at local time noon.

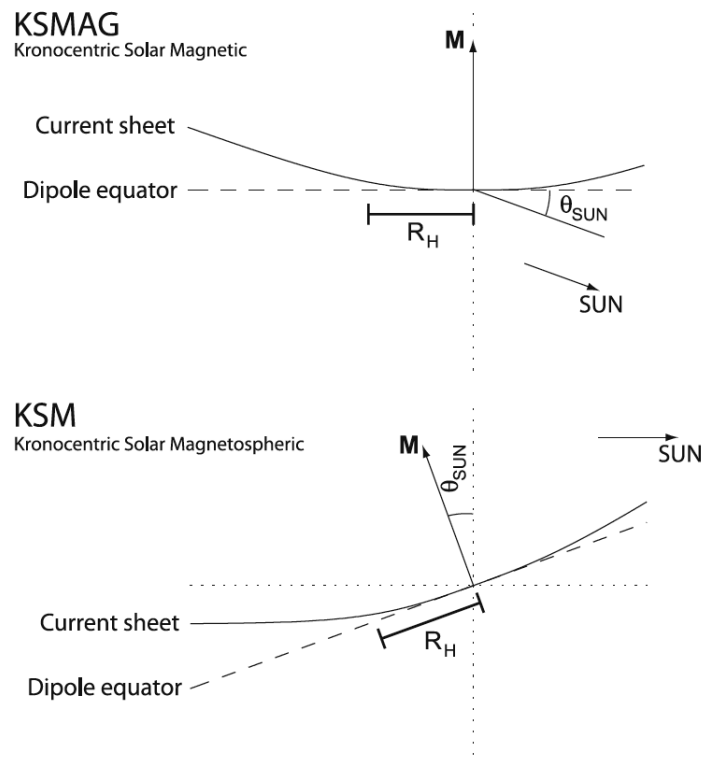


Figure 3.8: The KSM and KSMAG coordinate systems used for Cassini data analysis at Saturn. Figure from Arridge et al. [2008a].

Chapter 4

Quantifying the Stress of the Saturnian Magnetosphere During the Cassini Era

The large-scale structure of the Saturnian magnetosphere is modified by both internal and external processes. The 13-year Cassini mission covered elements of both Saturn seasons and two solar cycles, and had significant spatial coverage of the magnetosphere. In this chapter, we will use the Cassini magnetic field data to determine a stress state to track the global behaviour of the Saturnian magnetosphere during this era. We will also explore potential drivers of variability and define periods when the system was not in steady state.

At Earth, geomagnetic disturbances are measured using a range of different indices, with one of the most well known being the *Dst* (Disturbance storm time) index. The *Dst* index supplied by the World Data Center for Geomagnetism in Kyoto takes magnetic field measurements from ground-based magnetometers near the equator. The northward directed magnetic field of the Earth is depressed by the southward directed field due to the westward flowing ring current. Measuring deviations from a quiet state in

the longitudinally averaged B_z -component close to the equator is equivalent to measuring changes in the strength of the ring current. The Dst is essentially a measure of changes in the plasma pressure within the magnetosphere of Earth [Dessler and Parker, 1959, Sckopke, 1966]. An increase in the solar wind pressure produces a positive Dst as the field is compressed. Magnetic reconnection in the tail triggers an explosive conversion of magnetic energy to particle kinetic energy, where plasma is energised and accelerated planetwards creating intense aurora and enhancements of the ring current via injections of plasma. This enhancement of the southward ring current field produces a large negative Dst . Large deviations from the ground state indicate geomagnetic disturbances. For instance, $Dst < -50$ nT is indicative of moderate storm activity, but more extreme minimum values have been observed, as is shown in Figure 4.1. However, it should be noted that the Dst index has limitations and cannot capture all storm activity [e.g. Borovsky and Shprits, 2017].

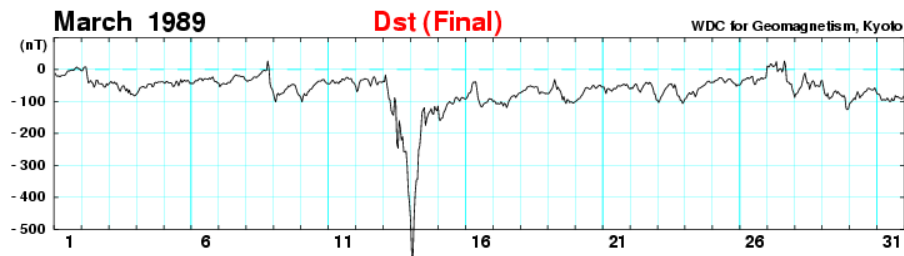


Figure 4.1: The Dst index from the World Data Center for Geomagnetism in Kyoto showing the March 1989 magnetic storm. This significantly low Dst index measurement indicates a super-storm and was the largest storm captured in the last 100 years. It resulted in significant ground-based disturbances to power systems including the electrical blackout of Quebec after its power grid lost power.

Russell et al. [2001] constructed an index tracking current sheet activity at Jupiter. They analysed data from low-latitude orbits from Pioneer, Voyager and Galileo to identify variability in the Jovian current sheet between

1975 and 2000. When determining the ground state to be subtracted from the data, they identified local time variation in the external field where it is more compressed at dusk compared to dawn. They found modest changes in the index between 1996 and 2000 with only a few examples of large-scale deviations from the ground state. Vogt et al. [2017] used a similar approach to calculate the spatial and temporal variability of the current sheet at Jupiter using Galileo data from 1996 to 2003. They similarly identified the dawn-dusk asymmetry observed by Russell et al. [2001]. They also found that the strength of the current sheet varied by only 15-20% of its average state during this period. They attempted to link the changes in the current sheet with known drivers of variability. Comparing outputs from the Zieger and Hansen [2008] one-dimensional solar wind propagation model with the strength of the current sheet, they found little evidence of solar wind influence. This is in contrast with the stronger correlation between magnetopause standoff distance and current sheet properties identified at Saturn by Bunce et al. [2007].

In this chapter we aim to determine a similar stress state at Saturn based on the variable strength of the magnetodisc current sheet. The current sheet at Saturn is often referred to as the ring current with reference to the terrestrial system. However, Saturn is rotationally-dominated and the plasma populating the current sheet is internally sourced, hence why we do not refer to it as the ring current.

This study takes influence from Leisner et al. [2007] who determined a stress index for Saturn based on the first 27 orbits of Cassini. They constructed a global magnetic field model using these orbits to determine the average quiet state. They determined the stress index for each orbit by selecting equatorial data close to the planet, since ground-based measurements are of course unavailable at Saturn, and subtracted the model to identify perturbations away from the ground state. They found that in general, the system remained close to its ground state, but observed a few

large-scale deviations. They also observed a day-night asymmetry, where processes in the tail produces signatures restricted to the tail region that affect the determination of the stress index close to midnight.

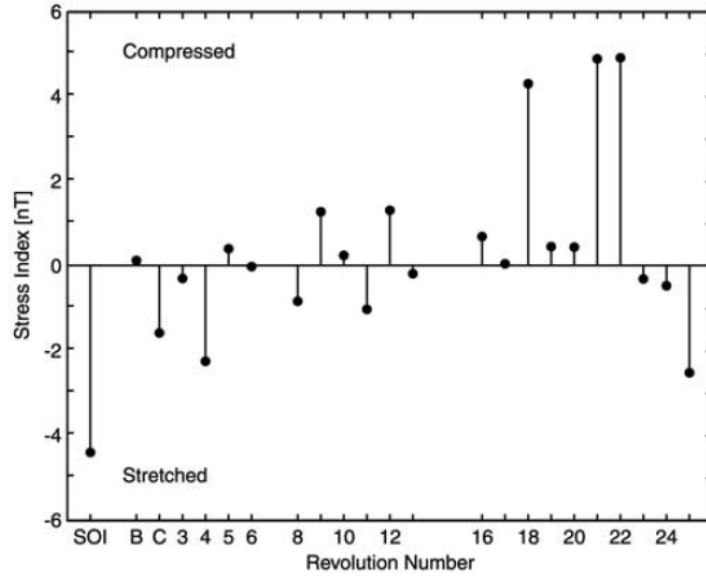


Figure 4.2: Figure from Leisner et al. [2007] showing stress indices they calculated for the early Cassini mission. They found that the system remains close to its ground state, but occasional large-scale deviations are observed where the system is significantly compressed or expanded.

For our study, we will quantify a similar stress state to track the global configuration of the Saturnian system. We will use the CAN magnetodisc model [Connerney et al., 1983] to measure deviations in the magnetodisc current sheet close to the planet. We will construct a ground state based on data from the entire Cassini mission to understand the underlying spatial distribution of the current. We will use the stress state to identify when the system was significantly expanded or compressed, as well as identifying cases when the current sheet was not steady, implying that a reconfiguration event has probably occurred that is not captured by the model.

Work from this chapter contributed to the publication of Staniland et al.

[2018].

4.1 Stresses acting on the Magnetosphere

The magnetopause boundary is the point of stress balance that separates the Saturnian magnetosphere from the interplanetary magnetic field. Stresses that are both internal and external to the magnetosphere act to either expand or compress the system. This chapter will study changes in system size and attempt to determine the stresses that are causing these global changes.

The external stress modifying the Saturnian magnetosphere is the incoming solar wind [Jackman et al., 2004]. The supermagnetosonic plasma flowing radially away from the Sun drags the IMF which compressed the dayside magnetic field at Saturn and is deflected around around the obstacle. Since Saturn orbits at 9 times the distance to the Sun compared to the Earth, properties of the solar wind differ. For instance, the solar wind magnetic field strength and density decreases with heliocentric distance. Nonetheless, the solar wind is highly variable even at large distances and increased upstream solar wind dynamic pressure compresses the Saturnian magnetosphere, pushing the magnetopause subsolar stand-off point towards the planet [Jackman et al., 2005, Arridge et al., 2006]. The dayside field geometry of Saturn can be compressed into a quasi-dipolar configuration under high pressure upstream solar wind conditions, creating a day-night asymmetry in the magnetodisc geometry [Arridge et al., 2008b].

Internal stresses also modify the geometry of the Saturnian magnetosphere. Enceladus-sourced plasma radially stretches the magnetic field, perturbing the dipolar structure. The highly stretched field due to the outward centrifugal stress of the rotating plasma is balanced by an inward Lorentz $\mathbf{J} \times \mathbf{B}$ force (see Section 2.3.2 for further discussion). The inertial currents related to the corotating plasma dominates the current sheet

magnetic moment [Bunce et al., 2008] and so expansion of the field leads to a stronger current sheet whose outer edge is close to the magnetopause. Bunce et al. [2007] found a linear relationship between the solar wind dynamic pressure and current sheet strength, where the total current flowing through the current sheet increases with larger standoff distances. They also calculated B_{z0} , the north-south magnetic field component close to the planet, similar to the stress index we will calculate, finding a positive correlation where B_{z0} increases with increasing standoff distance. In addition, an increase in the energetic plasma pressure close to the magnetopause boundary can push against the solar wind dynamic pressure and act to inflate the magnetosphere [Pilkington et al., 2015a]. Tracking the variability of the magnetodisc current sheet between Cassini orbits acts as a proxy for the variability in system size. Hence, we will define the Saturnian stress state, an index that reflects whether the system is expanded, compressed or near its ground state, based on measurements of the current sheet close to the planet.

4.2 Quantifying the Stress State Index

We work in the Kronocentric Solar Magnetic (KSMAG) coordinate system as described in Section 3.3. We choose a region within the magnetosphere where the only expected contributions to the magnetic field are the internal field and the magnetodisc current sheet. Following the work of Leisner et al. [2007], we set our radial limit to be between $4.3 R_S$ and $6.3 R_S$. This is outside of the orbit of Enceladus and within the inner edge of the magnetodisc current, which is on average located at $\sim 7 R_S$ [Bunce et al., 2007]. Further analysis of the current sheet could be performed in the middle magnetosphere to study changes in the more disc-like region. However, this region is far more disturbed which makes determining a background state more difficult. Our chosen radial distance is within the steady mag-

netic region described by Leisner et al. [2005, 2007]. Our results are insensitive to these precise radial distances, provided we are within the inner edge of the magnetodisc current and outside the orbit of Enceladus. We restrict the data to be within ± 10 degrees of the magnetic equator to avoid high latitudinal current systems, such as the field-aligned currents which result in a bipolar disturbance in B_θ . We also eliminate segments of the trajectories that are within 45 degrees of midnight, similarly to Leisner et al. [2007], due to processes in the tail not captured by the model, such as reconnection and dipolarisations that locally modify the field.

In our chosen region, we subtract a model of the internal field from the data. The residual ΔB_θ component is parallel to the dipole axis at the equator and reveals the strength of the magnetodisc current. When the field is compressed (expanded) ΔB_θ will increase (decrease) as the magnetic flux is squeezed into a smaller (larger) region and the current sheet strength decreases (increases). The residuals ΔB_r and ΔB_ϕ in this region are up to an order of magnitude smaller than ΔB_θ , therefore we need only to focus on the latter. Within these restrictions, we have segments of 111 out of the total 294 orbits performed by the Cassini spacecraft between June 2004 and September 2017, which are plotted in Figure 4.3.

The internal field that is generated in the dynamo region within the planetary interior is present across all Cassini observations within the Saturnian magnetosphere. A model representation of this field must be subtracted from the data to identify contributions from external current systems. We use the ‘Cassini 3’ model given by Dougherty et al. [2005]. Higher order contributions are unnecessary due to our chosen radial distance, where these coefficients have a magnitude the order of the magnetometer noise level [Cao et al., 2012]. At these distances, use of a different internal field model such as the Dougherty et al. [2018] model will also not affect our results.

To describe the magnetodisc current, we use the CAN disc model Con-

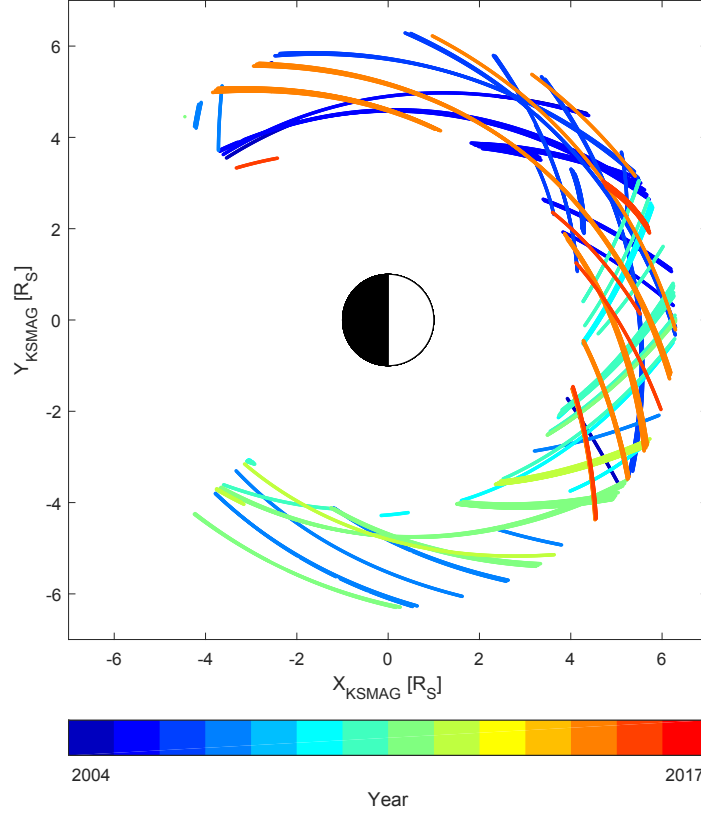


Figure 4.3: The Cassini trajectories segments across the complete mission that were within our chosen region, plotted in the XY-plane with the axis normalised to Saturn radii. The trajectories are contained within ± 10 degrees of the magnetic equator and are not within ± 45 degrees of midnight. The color represents the year. Note that some orbital segments lie on top of each other. Figure from Staniland et al. [2018].

nerney et al. [1981b, 1983] outlined in Section 2.3.2. In this model, the current density decreases with radial distance from the planet as $1/\rho$ and is vertically uniform within the magnetodisc, such that the product $\mu_o I_o D$ is proportional to the width-integrated (along the z -direction) current density. This current system produces a magnetic field that opposes the internal field, depressing B_θ . We will use the analytic approximation for

the magnetodisc current field components near the center of the annulus. These are given by

$$\begin{aligned} B_{\rho,i} &= \frac{\mu_0 I_0 \rho}{4} (F_1^{-1} - F_2^{-1}) \\ B_{z,i} &= \frac{\mu_0 I_0}{2} \left[2D (z^2 + i^2)^{-1/2} - \frac{\rho^2}{4} \left(\frac{z - D}{F_1^3} - \frac{z + D}{F_1^3} \right) \right], \end{aligned} \quad (4.1)$$

where $i = a, b$ is the current sheet inner and outer edge and

$$\begin{aligned} F_1 &= [(z - D)^2 + i^2]^{1/2} \\ F_2 &= [(z + D)^2 + i^2]^{1/2}, \end{aligned} \quad (4.2)$$

and we subtract the field components calculated using the inner edge from those calculated using the outer edge to determine the field generated by the finite current sheet. We then coordinate transform these to find the meridional B_{θ} component due to the current sheet. These approximations are in good agreement with the numerical formulations, except for certain regions including at the inner edge of the magnetodisc current [Edwards et al., 2001]. However, since we will fix the inner edge to be $\sim 8R_S$, our chosen region is well inside of this limit and so the analytic formulations will suffice. The other effect we might need to consider is the seasonal warping of the current sheet above and below the magnetic equator due to the changing dipole tilt angle with respect to the Sun [Arridge et al., 2008a]. However, the hinging distance at which the current sheet curves out of the magnetic equator into a ‘bowl’ shape ranges from 15 to $30R_S$, far outside our region of interest. The contributions to the magnetic field due to this deformation are minimal in our chosen region and so we can assume the centre of the current sheet is co-located with the rotational equator.

4.2.1 Model Fitting Procedure

The stress state index is a numerical scale that allows us to compare the global structure between Cassini orbits with a single number. We aim to fix three of the current sheet parameters and fit the model to the data by optimizing the remaining parameter to the residual field. Changes in this parameter can be quantified as the stress index. We used revolution (Rev) 50 as an example orbit due to its minimal background variability in the magnetic field data and low local time coverage to test the sensitivity to initial conditions of the fitting procedure and the threshold for convergence of each parameter. The magnetic field data from Rev 50 is shown in Figure 4.4 having fixed the current sheet inner and outer edges as an example. We then test the sensitivity of the model fit to the different combination of chosen fixed parameters and these results are shown in Figure 4.5.

Figure 4.5 shows that fixing $\mu_o I_o$ either by itself or with another parameter had the highest sensitivity to our initial condition, giving the largest root-mean-square (RMS) error when the parameter was fit using different initial guesses. We therefore choose $\mu_o I_o$ to represent the stress index of the system. We fix the half-thickness, inner and outer edges to be $3R_S$, $8R_S$, and $15.5R_S$, respectively [Connerney et al., 1983]. Our choice of these values does not affect the result, provided that the inner edge of the magnetodisc current is outside our defined region. Note that we are not giving a full description of the magnetodisc current sheet, which involves constraining all four parameters. Instead we are tracking the strength of the magnetodisc current sheet by measuring perturbations in $\mu_o I_o$ in a region where contributions to the magnetic field are primarily from the internal field and this current system. The units of I_o are current per unit length, so multiplication with μ_o give us units of nT. Hence, the stress index will be in units of nT, the same as $\mu_o I_o$.

For each Rev, we fit $\mu_o I_o$ to the residual magnetic field data using a non-linear least squares regression solver. Beginning with a suitable initial con-

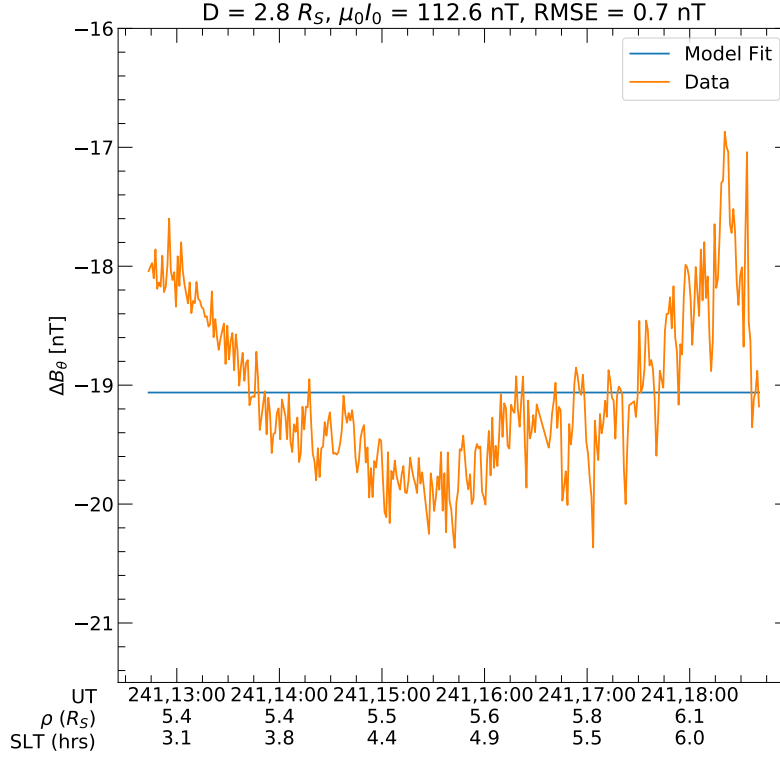


Figure 4.4: The residual B_θ magnetic field component for Rev 50 is shown in orange, having subtracted an internal field model. This figure shows a single example of the model fitting procedure having chosen some combination of the parameters to be fixed, which in this case are the current sheet inner and outer edges. The fitted parameters are shown at the top along with the root-mean-square error (RMSE) of the fit.

dition, chosen to be 60.4 nT based on Connerney et al. [1983], Equations 4.1 are fit to the data by iterating values of $\mu_0 I_0$ to find the minimum of the sum of the square residuals between the model and the data. For each Rev, we will then have an associated $\mu_0 I_0$ value and RMS error which will reveal the state of the system and how well it is described by the steady state current sheet model.

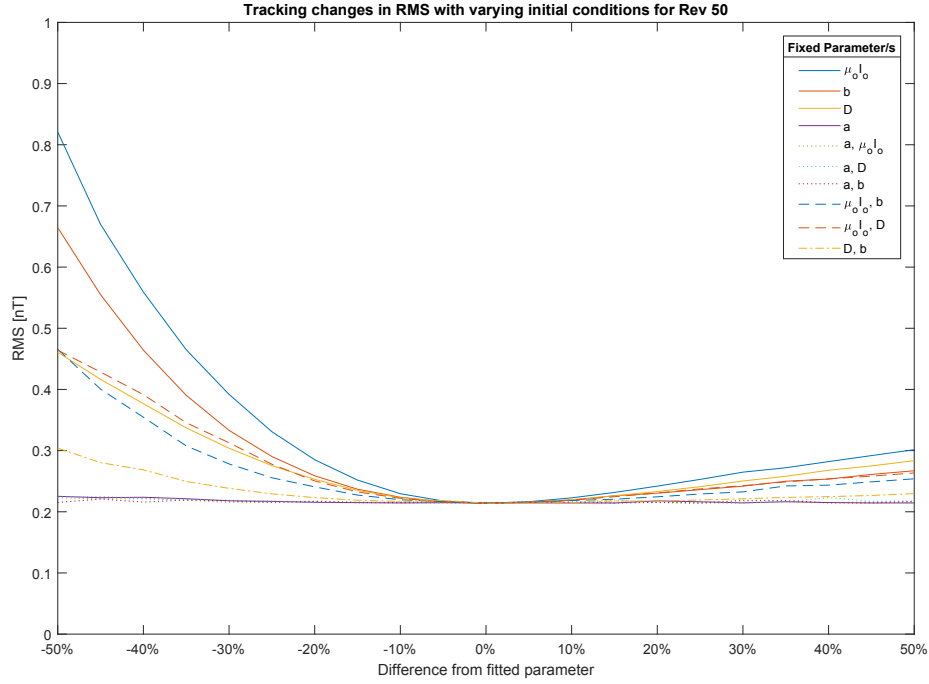


Figure 4.5: We fix each of the four current sheet model parameters either by themselves or with another parameter to identify which parameter the model is most sensitive to. The x-axis shows if we vary the fixed parameter by either increasing or decreasing it, whilst the y-axis shows the root-mean-square (RMS) error associated with each fit. This shows that when we fix the current intensity parameter $\mu_0 I_0$, the RMS error from fitting the model by varying the other three parameters is highly sensitive to the initial choice of $\mu_0 I_0$. The next most sensitive parameter the model fit is most sensitive to the outer edge of the current sheet, denoted as b . Since we want a single value to compare between orbits, we fit all parameters except $\mu_0 I_0$ and track how this varies.

4.3 Results and Discussion

An example of the model fitting procedure is shown in Figure 4.6. For Rev 141, the fitting procedure gave an RMS error of 0.37 nT. For Rev 147, the fitting procedure gave an RMS error of 2.18 nT. These two cases are markedly different, with the former being well described by the static model, whilst

the latter is not. During Rev 147, Cassini passed through the current sheet whilst it was in a non-steady configuration. We see in Figure 4.6 clear examples of injection events between $\sim 3 - 4$ am local time. We found these were also picked up in the Azari et al. [2018] catalogue of injection events. We see that the field is more expanded than expected until around 7.8 am local time (in decimal hours) when the field becomes more compressed than we would expect. This configuration is not well described by the model.

We define a steady state threshold for the magnetodisc current sheet to identify passes where the stress value is representative of a perturbation from the ground state, and passes when an event occurred which cannot be captured by the model. A larger RMS error will mean that during this pass the magnetodisc current sheet was further from being steady state.

The RMS errors for the 111 orbital passes through our region have a non-Gaussian distribution with clear outliers. These can be observed in Figure 4.7. We set a conservative threshold for a steady state current pass to be when the RMS error is less than 1 nT. Approximately 62% of the available passes fulfill this criteria, whilst the rest have an average RMS error ~ 1.4 nT, with the largest value being ~ 2.9 nT. The range of fitted $\mu_0 I_0$ values is also shown in Figure 4.7, ranging between $\sim 30 - 90$ nT, with a mean value of 66.7 nT.

Distinguishing between spatial and temporal variability is particularly difficult. Giampieri and Dougherty [2004] modelled the magnetodisc current sheet for all spacecraft passes of Saturn in the pre-Cassini era. They found that using different model parameters for the inbound and outbound segments significantly improved the model fits which suggests a local time variability. However, you cannot separate the spatial and temporal effects during a single orbit. Having the complete Cassini dataset provides the unique opportunity to identify whether there is an underlying spatial trend at Saturn. Local time asymmetries have been identified in the rotation-dominated magnetosphere of Jupiter across the tail [Kivelson et al., 2002].

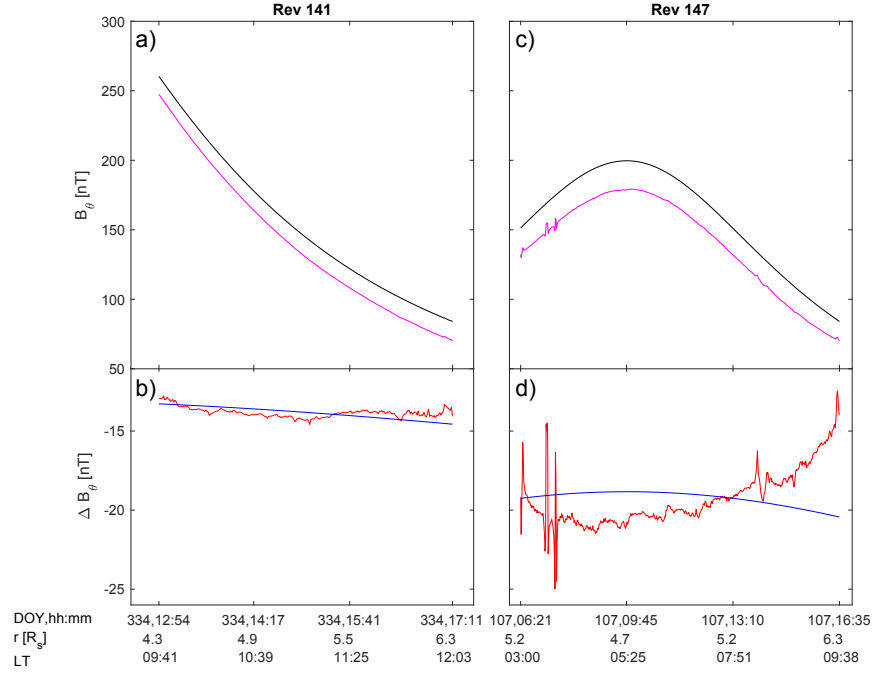


Figure 4.6: Magnetic field data collected by the Cassini spacecraft within the region outlined herein. Panel a) shows for Rev 141 the observed B_θ (magenta) and the ‘Cassini 3’ internal field model (black) as functions of time. Panel b) shows ΔB_θ (red) and the Connerney et al. [1983] magnetodisc current model plotted on top (blue), both as a functions of time. The fitting procedure calculated $\mu_o I_0$ to be 66.7 nT with an RMS error of 0.37 nT. The same is shown in panels c) and d) for Rev 147, where $\mu_o I_0$ was found to be 92.4 nT with an RMS error of 2.18 nT. Figure from Staniland et al. [2018].

The field lines are more stretched at dawn than dusk, implying the field is more compressed at dusk, leading to a cross-tail asymmetry in which the tail current sheet is thicker at the dusk flank than the dawn flank. A dawn-dusk asymmetry has been identified for the magnetopause of Saturn [Pilkington et al., 2015b]. The boundary was found to be 7% farther from the planet at dawn compared to dusk. This is likely due to a force balance, with the flow of the co-rotating plasma being parallel to the external solar wind flow at dusk and anti-parallel at dawn.

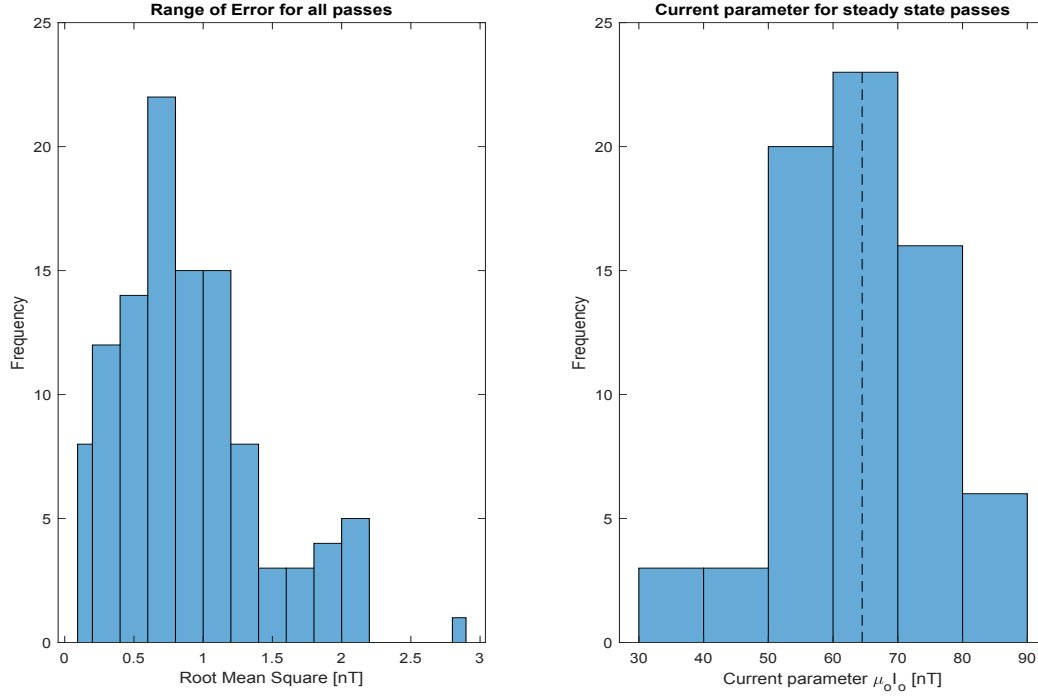


Figure 4.7: The left histogram shows the distribution of root-mean-square (RMS) errors for our 111 orbits. The right panel shows the distribution of $\mu_0 I_0$ values for our steady state cases where the RMS error < 1 nT.

To determine whether there is an underlying spatial dependence, Figure 4.8 plots the average $\mu_0 I_0$ per local time. We only use steady state passes to remove unreliable $\mu_0 I_0$ values associated with the non-steady state intervals. The black line represents the mean current parameter per local time, calculated by assigning the fitted $\mu_0 I_0$ of each orbital segment to the local time they covered. This is valid provided we are only using steady state passes where the fitted parameter is representative of the magnetic field. The light grey error bars are the standard deviation of $\mu_0 I_0$ at each local time minute, whilst the dark grey error bars are the standard deviation in the mean / standard error. The results reveal a local time dependence, where the average current parameter in the near midnight sector is higher, implying that the magnetodisc current strength is increased and so the field

is more stretched than in the near noon sector, which is on average more compressed with a lower magnetodisc current strength. This correlates with the day-night asymmetry that arises due to the dayside magnetodisc geometry being suppressed by the dynamic solar wind pressure [Arridge et al., 2008b]. We further find that the average $\mu_o I_o$ at dusk is smaller compared to dawn, indicative of a more compressed regime at dusk compared to dawn. This reflects the global characteristic of the dayside magnetosphere where the magnetopause is closer to the planet at dusk compared to dawn [Pilkington et al., 2015b].

The average standard error at each local time minute is ~ 8 nT, whilst the range of the mean local time current parameter values is ~ 25 nT, implying that on average the spatial variability is more significant than the temporal variability. Note that if we divide $\mu_o I_o$ by -4 this gives us the approximate value of B_θ that the model was fit to. Nonetheless, the errors bars in Figure 4.8 reveal that whilst there is a resolvable spatial trend, temporal variations will also influence the stress index, resulting in deviations from the local time average.

To quantify the stress index, we define a ground state that represents the magnetosphere in a ‘quiet’ state by using the mean $\mu_o I_o$ local time values calculated above, thereby accounting for the spatial dependence. The steady state current parameter values are binned into 3-hour local time sectors, starting at approximately 03:00 and finishing at approximately 21:00. The ground state is calculated within these bins from Figure 4.8 by selecting values within the dark grey region. The ground state has a minimum in the 12:00-15:00 sector of ~ 60 nT and a maximum in the 06:00-09:00 sector of ~ 81 nT, with an average of ~ 70 nT. The ground state is shown in Figure 4.8. Setting the RMS error threshold for a steady magnetodisc current pass to be 1 nT does not significantly alter our ground state. Increasing or decreasing the threshold marginally varies the average ground state by ~ 2 nT, predominately being modified near dawn.

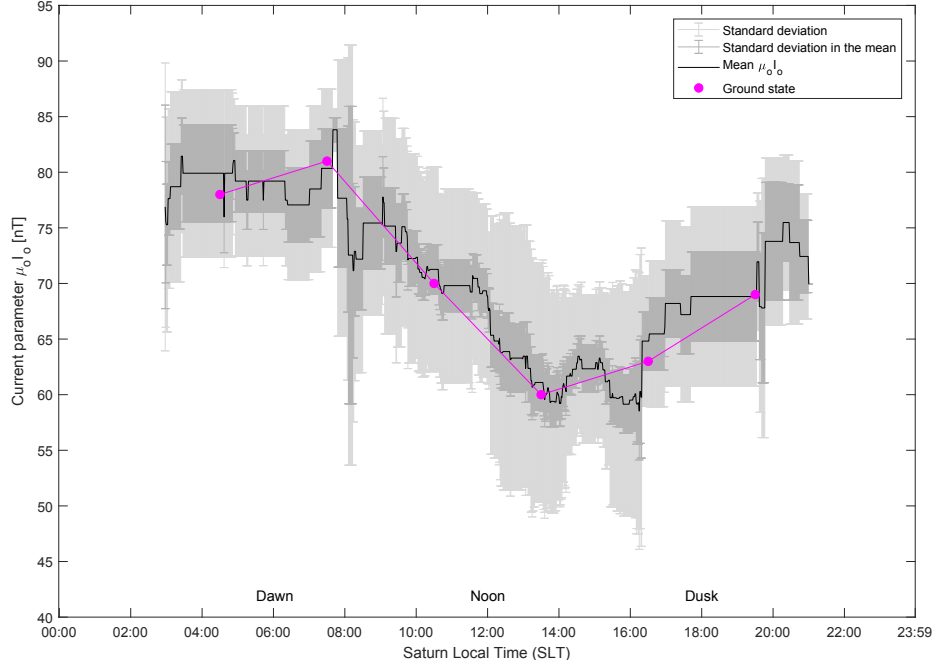


Figure 4.8: The mean current parameter $\mu_o I_o$ for all steady state passes is presented (black) as a function of Saturn Local Time (SLT). The light grey error bars are the standard deviation of the current parameter values at each local time minute. The dark grey error bars are the standard error. The magenta dots represent the 3 hour binned ground state. Figure from Staniland et al. [2018].

To determine the stress index, we calculate the average difference between the local time corrected ground state and the $\mu_o I_o$ value calculated for each orbital pass through our region. The results are presented in Figure 4.9. A positive stress value indicates the magnetic field was stretched, whilst a negative stress value indicates the field was compressed. The results show that in general the magnetosphere was almost equally either in a stretched or compressed configuration. However, there were slightly more compressed stress index values than stretched between Saturn Orbital Insertion (SOI) and 2008.

Approximately 75% of the steady state passes have a stress value less

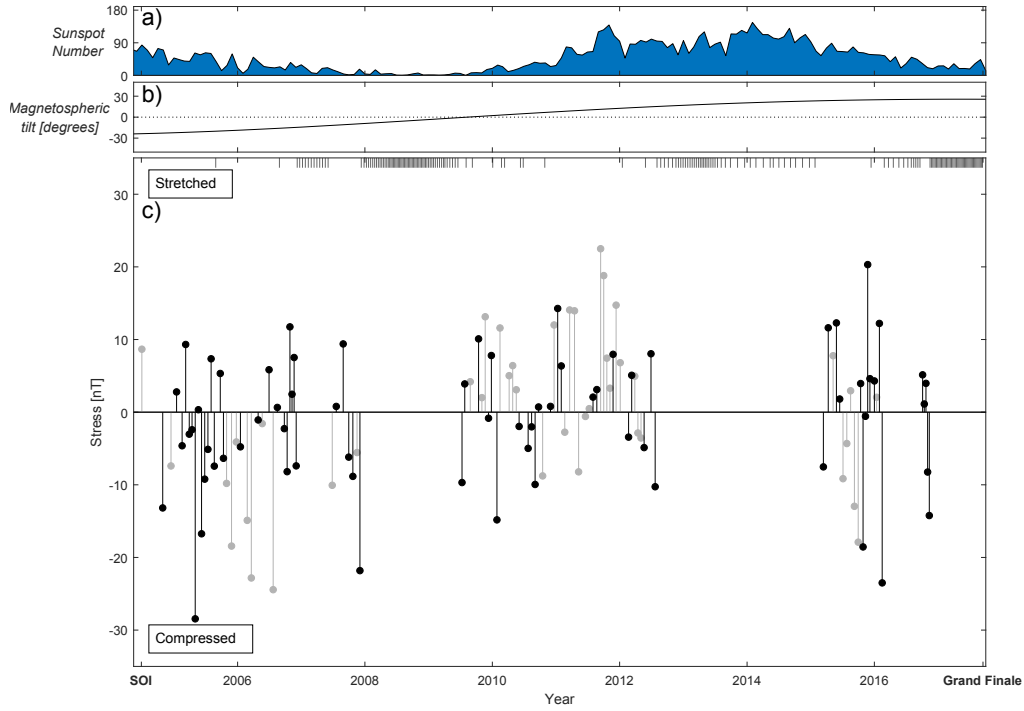


Figure 4.9: The stress values calculated for the Saturnian magnetosphere during the complete Cassini mission. Panel a) shows the solar cycle during this era, compiled by counting the average number of sunspots per month (Source: WDC-SILSO, Royal Observatory of Belgium). Panel b) shows the tilt of the dipole equator with respect to the Sun, where a change of sign represents the change in season. Panel c) shows the stress values calculated for each Cassini orbit. The black stems represent steady state orbital passes, whilst the grey stems are non-steady state passes. The ticks along the top edge of the panel c) indicate Cassini orbits not used for this study due to being outside our region of interest. Figure from Staniland et al. [2018].

than ± 10 nT. Solar wind compression of the magnetosphere reduces the magnetodisc current parameter $\mu_o I_o$ by 2 to 8 nT and perturbs the system for a period of the order minutes to a day, in accordance with these measured compressions [Jackman et al., 2004, Leisner et al., 2007]. The standard deviation in the steady state stress values is ~ 10 nT. Whilst the mag-

netosphere spent a significant period at or near its ground state, Figure 4.9 also shows evidence of large-scale perturbations occurring to the system. During the interval that Cassini passed through our region, the configuration of the magnetosphere was modified but the system remained in a steady state. For instance, on 28th October 2015 a significant compression was observed between quiet conditions, with a recorded stress value of -18.6 nT. The temporal spacing of the Cassini orbits at this time is ~ 2 weeks. The largest compression event observed had a stress index value of -28.4 nT. On 23rd November 2015 the magnetosphere was recorded to be at its most stretched, with a stress value of 20.3 nT. These large scale perturbations are evidence of the dynamical nature of the Saturnian magnetosphere, increasing and decreasing its stress index by almost half the magnitude of the average ground state.

We isolated the stress index into local time sectors to search for seasonal dependence. During the Cassini mission, Saturn underwent a change from southern to northern summer, with vernal equinox occurring in August 2009. We were unable to identify any clear seasonal trend, but this is not wholly unexpected. The processes that modify the stress index do not all share seasonal variability. Whilst Enceladus has variable outgassing, for instance due to tidal forces opening the ‘tiger stripes’ [Hedman et al., 2013] a seasonal dependence has not been observed. The rings of Saturn do have a seasonal atmosphere and are a plasma source, but to a much lesser extent than Enceladus which dominates this process [Tseng et al., 2013, Persoon et al., 2015]. An observed seasonal variance is the northward and southward warping of the current sheet from the magnetic equator [Aurridge et al., 2008a]. However, a vertical distortion does not necessitate variability in the stress index. Seasonal variability exists in the magnetosphere but it is not necessarily linked to the stress index, or correlated between processes, and so the lack of an overall trend is unsurprising.

4.4 Nightside Stresses

To ensure that our exemption of the midnight data was valid, we perform the same analysis on the excluded data. In Figure 4.10 we show Cassini trajectories that are within 10 degrees of the equatorial plane and between $4.3 - 6.3R_S$ except we now analyse segments exclusively within 45° of midnight. There is good coverage in this region that spans the entire Cassini mission.

We fit $\mu_o I_o$ to the residual field measured during each pass of our region to identify the strength of the current sheet. The results are shown as a function of local time in Figure 4.11, in which the new results are shown alongside the previously calculated local time values. On average, the current parameter is approximately 77 nT in the 45° window around midnight and remains reasonably constant between 21-3 LT. The field is consistently expanded close to midnight, an expected result since the field can freely stretch downtail. However, there is also significant variability showing the nightside configuration is not steady.

We find 69 revs that pass through both the original region chosen and within 45° of midnight. We compare the fitted $\mu_o I_o$ parameter between these regions. In Figure 4.12 we have plot the $\mu_o I_o$ calculated in either local time sectors for each of these orbits, which we for the moment distinguish as dayside and nightside. If a point lies on the diagonal then the state of the system in the tail is the same as the rest of the data during that orbit. We would assume that this would be more likely for the orange points that show cases where the current sheet was in steady state. However, we see no such trend. In fact, at a given value for the dayside $\mu_o I_o$ the nightside $\mu_o I_o$ can be found either side of the diagonal. For instance, in Figure 4.12 when the dayside $\mu_o I_o \approx 92\text{nT}$, we see that the nightside $\mu_o I_o$ can equal either 80 nT, implying the nightside is more compressed, or it can equal 100 nT, implying that it is more expanded. Hence, the assumption to exclude this region from our calculation of the stress index was valid, as was also

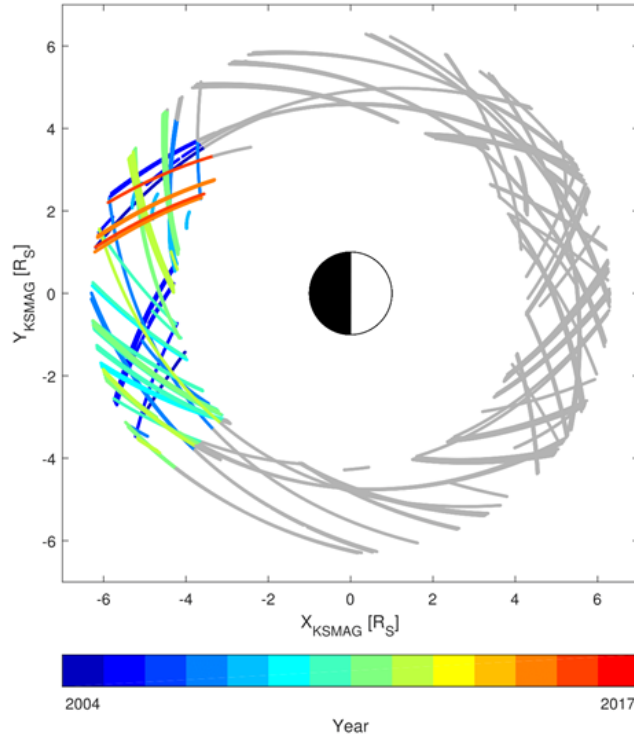


Figure 4.10: The Cassini trajectories that pass through 45° of midnight which had originally been removed from our analysis are shown, with the colour representing the time of year UTC. The grey passes are those used in the original study.

assumed by Leisner et al. [2007].

4.5 Comparing Stress Index Variability to Potential Drivers

We want to explore some of the potential drivers of stress index variability at Saturn. Bunce et al. [2007] showed that the current sheet parameters vary with changes in the subsolar standoff distance. The external stress that plays a role in determining the size of the system is the solar wind.

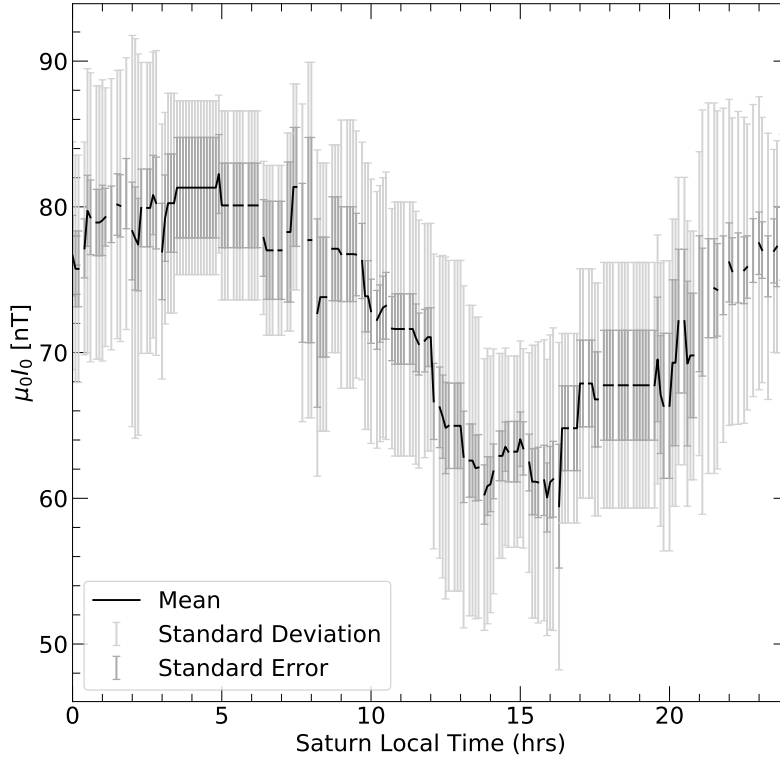


Figure 4.11: The same plot as Figure 4.8 but now including the data close to midnight.

At the outer planets, predicting the behaviour of the solar wind and how it influences internal dynamics and structure is difficult due to the lack of upstream monitors alongside in-situ measurements from orbiting satellites. However, models that use solar wind parameters at 1 AU and propagate them throughout the solar system provide a reasonable assessment of the local solar wind properties at Saturn. One-dimensional MHD models [e.g. Tao et al., 2005, Zieger and Hansen, 2008] output values for key solar wind parameters, such as dynamic pressure and velocity, at a given solar system position. These are most reliable during apparent opposition - when the Sun, input and spacecraft you use are aligned, accounting for the time delay for solar wind arrival between 1 AU and the spacecraft. These

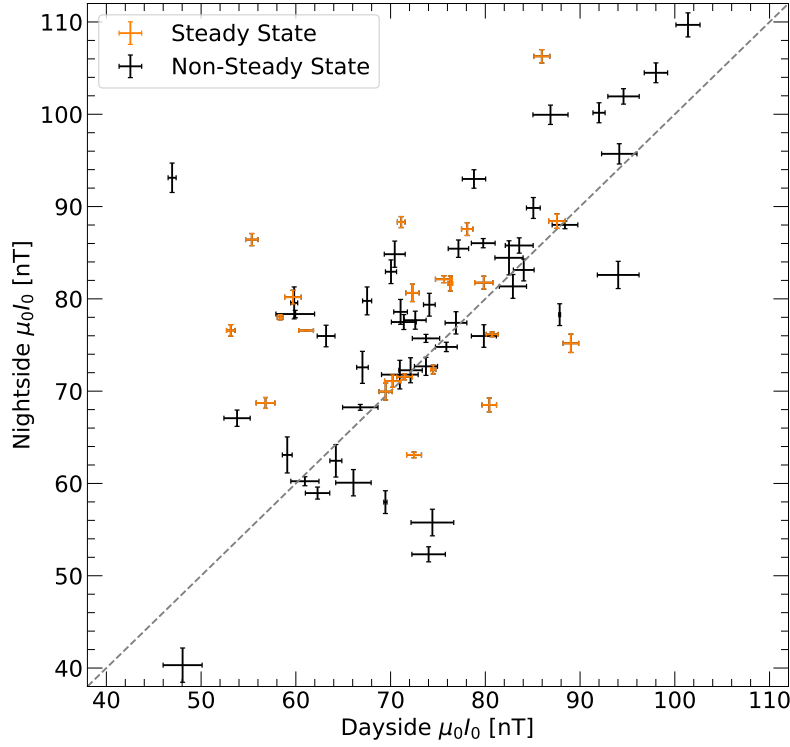


Figure 4.12: Comparing $\mu_0 I_0$ calculated for Revs that pass through both our original region chosen and within 45° of midnight, which for now we just refer to as dayside and nightside. The width of the errorbars represented the RMS error associated with the model fit. The orange errorbars show revs where both dayside and nightside fits were steady state. The black errorbars show revs where either the dayside or nightside was non-steady state. Since all the datapoints do not lie along the diagonal, we see there is a clear difference between the dayside and nightside, hence justifying our exclusion of this region in our analysis.

models are also reliable during times of high recurrence index - when the solar wind is steady on the time-scales of a solar rotation (e.g. the declining phase of the solar cycle). When both of these criteria are fulfilled, the propagated values for the solar wind are most reliable, with shocks arrival time errors as low as 10-15 hours [Zieger and Hansen, 2008]. We can also compare sunspot activity to the stress index.

The internal stresses acting on the system are the variable outgassing of Enceladus and the presence of suprathermal plasma in the outer magnetosphere that acts to inflate the magnetosphere [Pilkington et al., 2015a]. The system can be either plasma-loaded or plasma-depleted and this affects how it responds to changing solar wind conditions [Hardy et al., 2020]. Since we calculate the stress index close to the planet, we cannot compare directly to conditions in the outer magnetosphere where the suprathermal plasma pressure is large enough to push back against the solar wind dynamic pressure. We also do not have continuous measurements of the outgassing rate at Enceladus, although we might not expect this to be particularly insightful considering the delay between the production of neutrals and plasma at Saturn [Bagenal and Delamere, 2011]. Interchange events are signatures of parcels of hot plasma being injected into the inner magnetosphere, whilst the cool plasma is able to diffuse outwards, a process that conserves magnetic flux and enables internally sourced plasma to be eventually lost from the system. The magnetosphere is centrifugally unstable due to the outward forcing of plasma sourced from Enceladus. We can test whether there is a response mechanism between the state of the system and the occurrence of interchange events. We will use the Azari et al. [2018] catalogue of interchange injections calculated from H^+ flux intensifications seen in the CHarge Energy Mass Spectrometer (CHEMS) H^+ data.

In Figure 4.13, we show a case study for Rev 23 where we study potential drivers of stress state index variability. The bottom two panels show the magnetic field measured when the stress index was determined, with the bottom panel showing ΔB_θ and the fitted current sheet model. We observe significant fluctuations in ΔB_θ that are not well captured by the model. For Rev 23 there is a large RMS error from the model fit, a generally large $\langle \Delta B_\theta \rangle \sim -9$ nT and a significantly compressed stress state index of -24 nT. This shows the system was highly compressed and undergoing a significant reconfiguration.

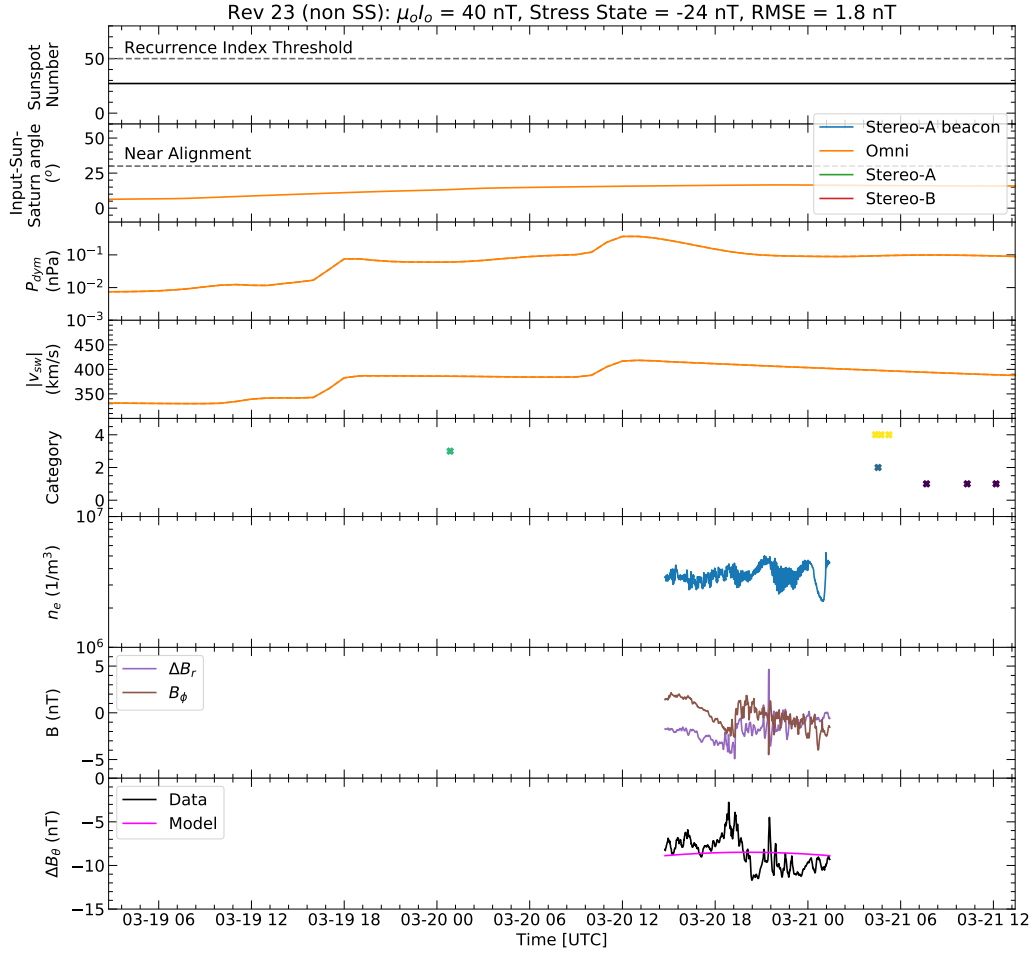


Figure 4.13: A case study comparing internal and external conditions to the stress index. This example is Rev 23, where we observe a significantly compressed regime (low stress index), but a large RMS error indicating the field was not steady state during this Cassini pass. The top four panels are parameters related to the solar wind, whilst the bottom four are in-situ Cassini data. A full description of the data shown is given in text. This case study is suggestive of a solar wind shock inducing perturbations to the magnetosphere, compressing the system and reconfiguring the field close to the planet.

We then compare the upstream solar wind properties for the preceding 36 hours plus following 12 hours, thus accounting for the approximate error in shock arrival time. The top panel of Figure 4.13 shows the monthly-averaged sunspot number (Source: WDC-SILSO, Royal Observatory of Belgium). The second panel shows the absolute angle (ranging 0-180°) between the Sun, the input source position and Saturn. The data used for input are from the Solar Terrestrial Relations Observatory (STEREO) mission, including the STEREO-A and STEREO-B spacecraft that orbit the Sun near Earth and the STEREO-A beacon, as well as data from the OMNI dataset that brings together data from multiple spacecraft to find the solar wind properties near Earth. We know that solar wind propagation models are most reliable during times of high recurrence index and apparent opposition. Hence we set a recurrence index threshold based on sunspot number, since recurrence index is highest during the declining phase and solar minimum, of 50 sunspots and a maximum absolute alignment angle of 30°. For Rev 23, data from OMNI can be used since it was below this threshold. The third and fourth panels show the dynamic pressure $P_{dyn} = \rho v^2$ and absolute velocity of the solar wind given by the Tao et al. [2005] propagation model. We see evidence of two sudden shocks, with an overall increase from $\sim 10^{-2}$ nPa to $\sim 10^{-1}$ nPa in the dynamic pressure. The fourth panel shows the interchange injection events detected by Azari et al. [2018], where the category of event runs from 1-4, with 1 being the least intense with respect to the background measured H^+ and 4 being the most intense. The fifth panel shows the in-situ electron density [Lewis et al., 2008] of the local plasma environment, where we see that $\langle n_e \rangle \sim 10^7$ m⁻³ which is close to the average electron density measured in this region.

Figure 4.13 could be suggestive of a large-scale compression of the system induced by a shock in the solar wind. This compression increases ΔB_θ in the inner magnetosphere and produces a large fluctuation in the stress state. The low RMS error with the fit and overall variability observed in

the magnetic field data in the bottom panels of Figure 4.13 could be due to compressional waves triggered by the shocks producing perturbations in the field as a response before the field recovers to a new equilibrium in a compressed state.

We present another case study with Rev 147 in Figure 4.14, where the layout is the same as Figure 4.13. For this example, we see that the stress state is significantly expanded at 15 nT but again with a large RMS error of 1.9 nT. The top panel shows that the monthly-averaged sunspot number is slightly larger than the recurrence index threshold. The second panel shows that both OMNI and STEREO-B are not aligned to trust the propagation model outputs, but that data from STEREO-A is close to alignment. The propagated solar wind data is shown in the third and fourth panels and is shown as a dashed line due to the unfavourable recurrence index and alignment, but since these values are close to our threshold we nonetheless discuss them. The fifth panel shows the presence of a significant number of interchange events observed [Azari et al., 2018]. This could suggest a process where an expanded system that is plasma-loaded triggers interchange. However, care should be taken since observations of injection events are highly circumstantial. Just because Cassini is observing more during a single orbit, due to their finite size, sporadic nature and the orbital sampling of Cassini, it is likely that many events were missed. Nonetheless, the low and steady solar wind dynamic pressure, coupled with the significant number of injection events observed could be linked to the expansion of the field and high stress index.

In Figure 4.15, we compare the derived parameters discussed above for all Revs used in this study. We find the parameters during the period we calculated the stress index plus 36 hours before. In this time range, we have calculated the total number of interchange events identified by Azari et al. [2018], the monthly-averaged sunspot number, the mean electron density, the mean solar wind velocity v_{sw} , the mean solar wind dynamic pressure

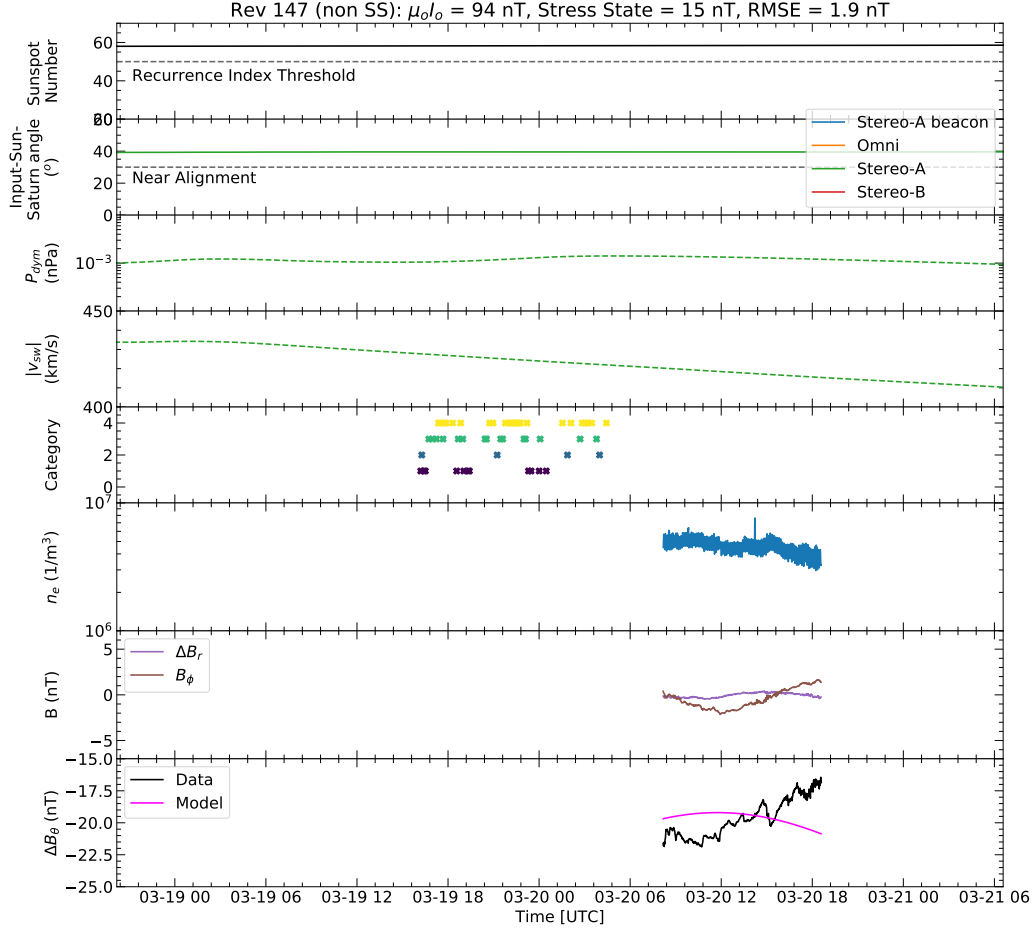


Figure 4.14: Comparing the possible drivers of stress index variability for Rev 147. The layout is the same as Figure 4.13, with the only difference being the propagated solar wind data in the third and fourth panels being shown as dashed lines to indicate that the input-Sun-Saturn alignment is larger than 30 degrees. This case study shows an example of an expanded system with low solar wind dynamic pressure coupled with a large number of injection events.

P_{dyn} and the change in dynamic pressure ΔP_{dyn} over this period to highlight if a shock or significant change in dynamic pressure was observed. In Figure 4.15 we plot each of these parameters against the stress index

and have performed a linear regression model fit, showing the statistical model in blue and 95% confidence interval in light blue. We also show the Pearson's r correlation coefficient, which is the covariance of two variables divided by their standard deviations and tells us the strength of the correlation. It varies between -1 and 1, where 0 implies there is no correlation, ± 1 implies perfect linear correlation and the sign tells us if the correlation is positive or negative. We have only included solar wind parameters when the input-Sun-Saturn alignment was less than 60 degrees to provide some protection from unreliable propagated data.

Figure 4.15 shows that whilst there is some apparent correlation between some of these parameters and the stress index, there is no statistically significant trend ($p > 0.3$). The parameters P_{dyn} and ΔP_{dyn} have higher r values, indicating an anti-correlation where we observe a more compressed magnetosphere when there is large P_{dyn} or ΔP_{dyn} (i.e. shocks). However, r is still particularly low with relatively large confidence intervals. Figure 4.15 also shows a weak correlation between sunspot number and stress index which might not have been initially expected. Jackman and Arridge [2011a] reported that at solar maximum more plasma would be produced in the Saturnian magnetosphere through an increase in photolytic reactions (photoionisation and photodissociation) in the Enceladus neutral torus. This could provide an internal driving mechanism for modifying stress balance and expanding the magnetosphere. However, the r value again for this correlation is low and we clearly observe significant scatter in the data. The other parameters show little to no correlation with the stress index. The above discussion shows that there are multiple factors affecting the global structure of the Saturnian system and the fact that we cannot identify absolute trends between these parameters and the stress index is not entirely unexpected.

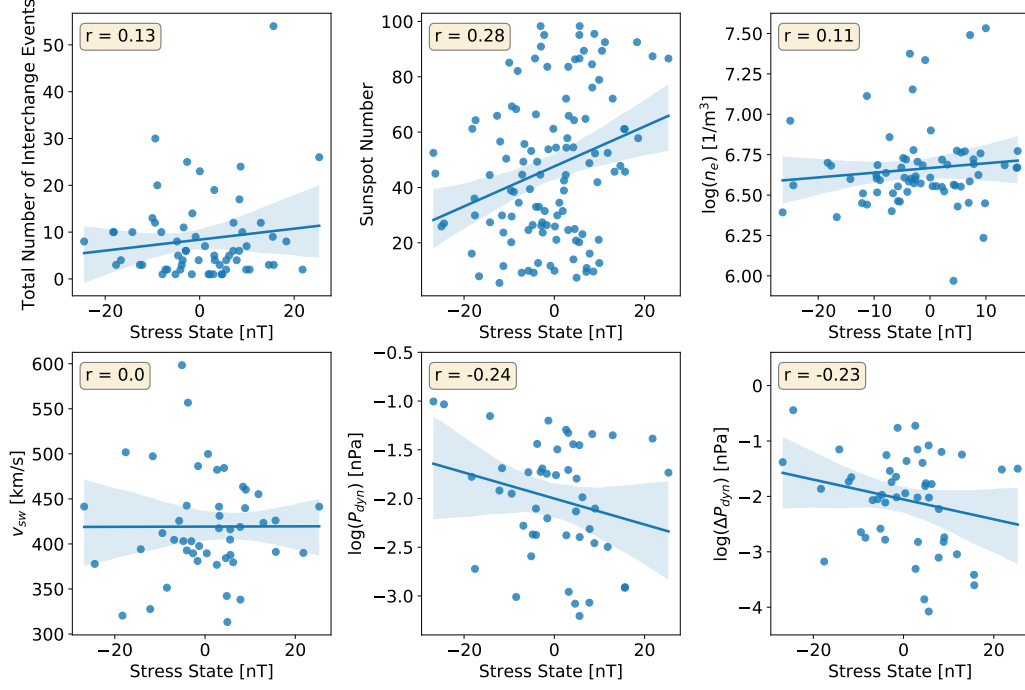


Figure 4.15: Exploring potential drivers of stress variability. Going from left to right, top to bottom, we compare the total number of interchange events, sunspot number, average electron density, solar wind velocity v_{sw} , solar wind dynamic pressure P_{dyn} and change in solar wind dynamic pressure ΔP_{dyn} during the period we measured the stress index and the preceding 36 hours. We only include data in the bottom three panels where the input-Sun-Saturn alignment is less than 60 degrees. We find weak correlation between the stress index and sunspot number, P_{dyn} and ΔP_{dyn} , but none of these are statistically significant.

4.6 Conclusions

Using magnetic field data collected by the Cassini spacecraft, we characterize the global characteristics of the Saturnian magnetosphere and its variation in time throughout the thirteen year Cassini orbital mission. We presented a quantitative analysis of the variation in time of the stress index of the Saturnian magnetosphere during the Cassini era. We fit the CAN

model to data when Cassini passed through the equatorial inner magnetosphere, a region where we expect the only magnetic field contributions to be from the internal field and magnetodisc current sheet. Deviations in the $\mu_0 I_0$ current intensity parameter reveal variations in the strength of the current sheet, and changes in the current sheet reflect changes in system size.

The results reveal that the magnetosphere spent a significant duration of the Cassini close to its ground state, whereby the stress index was close to 0 nT. However, large scale deviations were recorded throughout this period, indicating magnetic field reconfiguration events occurred, resulting in large stress indexes being observed, changing by ± 30 nT compared to the ground state. An examination of the stress values indicates that there is an underlying spatial variability, where the field is more compressed at noon and dusk compared to dawn. We also found that temporal variations drive changes in the stress index. A significant finding in this study was that $\sim 38\%$ of the orbits which passed through our chosen region were during a non-steady state interval. This provides useful information about the time scales over which the magnetosphere undergoes a reconfiguration and how often it occurs. The largest RMS errors were not due to the data containing both the inbound and outbound segments of a Cassini orbit, a scenario where modelling has shown to require different magnetodisc current parameters.

Potential driving mechanisms for stress index variability were briefly discussed. Two case studies were shown of a compressed and expanded case. These highlighted the different solar wind properties and internal environments. We were unable to find any general trends between the external and internal parameters we discussed. Whilst there was weak anti-correlation between solar wind dynamic pressure and pressure change with stress index, as well as correlation between sunspot number and stress index, none of these relations were statistically significant. This is not wholly

unsurprising as processes both internal and external to the magnetosphere of Saturn can modify the global structure. The interplay between internal and external drivers of dynamics is a key part of ongoing research of the large-scale structure of the Saturnian magnetosphere.

Chapter 5

The Nominal Thickness and Variability of the Magnetodisc Current Sheet

The presence of the magnetodisc current sheet shapes the global magnetic field structure of Saturn. In Chapter 4 we studied the strength of the current sheet, how it responds to changes in system size and what some of the drivers are for changes in global stress balance. Having discussed the radial extent, in this chapter we will focus on the thickness of the current sheet and how this shapes the large-scale structure of the Saturnian magnetosphere. The magnetosphere of Saturn and its different plasma populations are shown in Figure 5.1. The Enceladus-sourced ions populate the equatorial region and carry the azimuthal flowing current. We aim to study the thickness of the current sheet to constrain the large-scale structure of one of the most significant current systems in the magnetosphere. These results are essential for modelling the current sheet and provide better estimates for periods when Cassini observes the current sheet but does not pass directly through its edges. We further aim to characterise the large-scale asymmetries in the Saturnian system that reveal the dominant

drivers of variability.

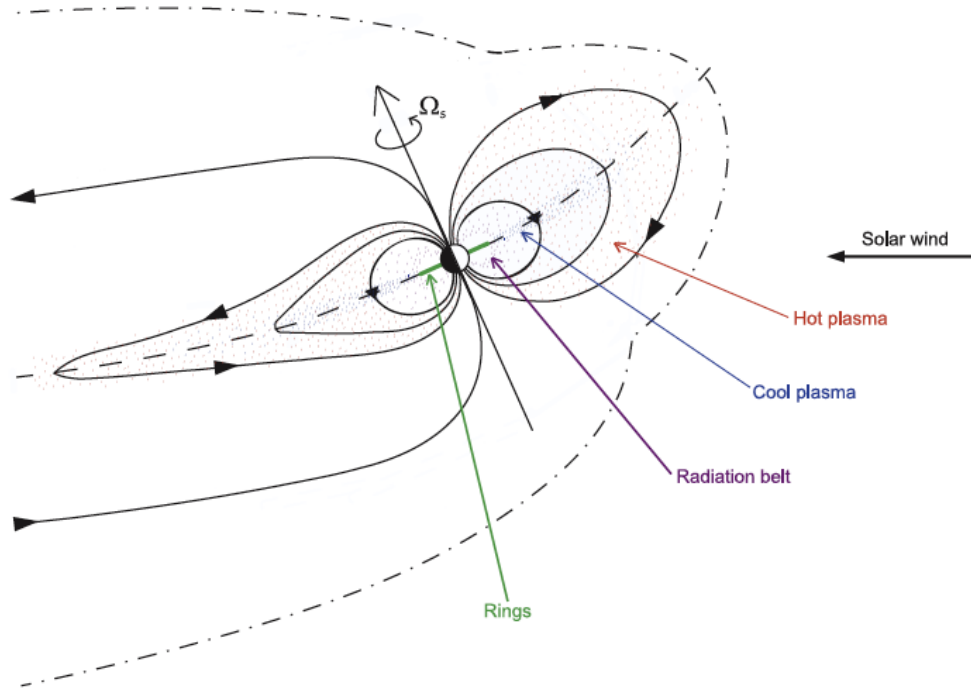


Figure 5.1: Sketch from Kellett et al. [2009] showing the magnetosphere of Saturn and its different plasma populations in the meridional plane during southern summer, with the solar wind flowing from the right. We see the cool plasma ($\sim$ eV) in blue that is sourced from Enceladus and is equatorially confined by the centrifugal force. The hot plasma shown in red ($\sim$ keV) that extends further up the field lines. The sketch also shows the rings and radiation belt in the inner region of the magnetosphere.

The thickness was initially calculated from flybys of Saturn by the Pioneer and Voyager spacecraft and was found to have a half-thickness of $\sim 2.5 R_S$ [Connerney et al., 1981b, Bunce and Cowley, 2003, Giampieri and Dougherty, 2004]. This value was obtained by fitting the Connerney et al. [1981a] model to the Voyager and Pioneer data. However, these spacecraft did not pass through both the northern and southern boundaries of the current sheet, and so the thickness was not uniquely determined. Kellett

et al. [2009] calculated the thickness directly by using six steep crossings of the current sheet made by Cassini in 2006 and 2007. They found that the half-thickness varied between $0.4 - 2R_S$, being thickest in the middle magnetosphere ($9-15 R_S$) and thinnest in the outer magnetosphere ($>15 R_S$) on both the dayside and the nightside. These results are shown in Figure 5.2. However, this study was performed early in the mission when there was a limited understanding of the temporal variability of the current sheet and so these features were solely attributed to a spatial dependence.

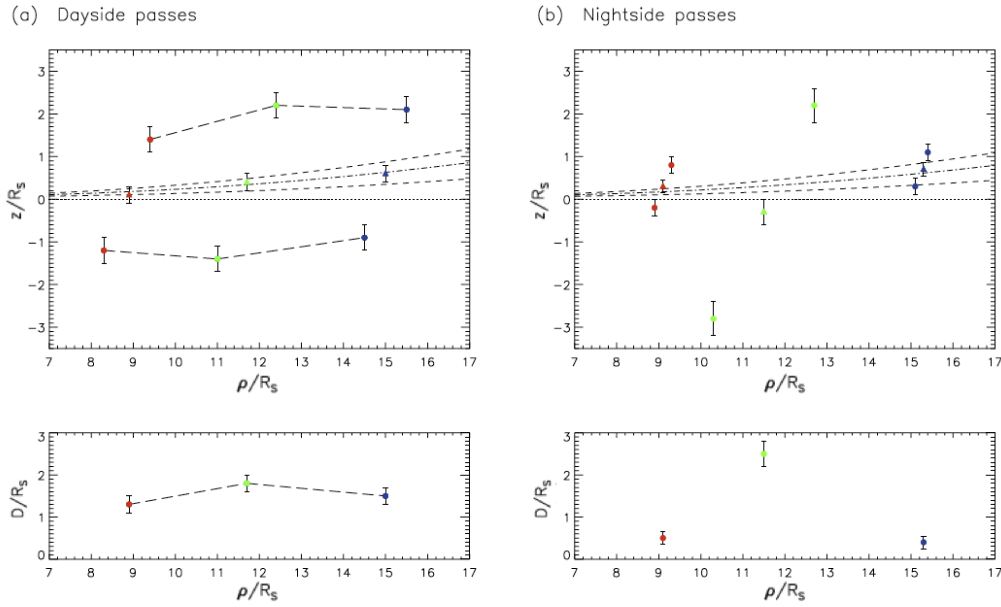


Figure 5.2: Plot from Kellett et al. [2009] showing their measurements of the current sheet thickness from six steep crosses of the layer during the early Cassini mission. The top two plots show the upper and lower boundary positions of the current sheet and its offset in cylindrical coordinates, along with the Arridge et al. [2008a] hinged current sheet model as dashed lines for three different hinging distances.

Sergis et al. [2011] determined the thickness of the magnetotail current sheet by fitting a Harris current sheet [Harris, 1962] to four steep crossings made by Cassini in 2007 and 2009. They identified a thin current sheet

with half-thickness $\sim 0.5 R_S$, embedded within a thicker plasma sheet with half-thickness $\sim 2.5 R_S$. They also found that the plasma thickness varied with different energies of particle populations and the scale-height of the plasma sheet has been found to reach as high as $7 R_S$ for H^+ ions [Thomsen et al., 2010]. This was understood in terms of the centrifugal scale height $\propto (k_B T/m)^{\frac{1}{2}}$ for a population of particles with temperature $k_B T$, where k_B is the Boltzmann constant and m is the particle mass [Hill and Michel, 1976]. This implies that the heavier, colder, ions would be constrained to the equator, whereas the hotter and more energetic plasma populations will be distributed further along the magnetic field lines. The focus of this study will be on the current sheet rather than the plasma sheet, and this can be identified using only the magnetic field data.

Staniland et al. [2018] tracked the strength of the current sheet throughout the Cassini mission and identified a local time asymmetry, revealing the field to be more compressed at dusk than dawn. Empirical models and simulations have also identified this asymmetry, showing a 5-10% difference in the location of the magnetopause at dawn and dusk [Pilkington et al., 2015b, Jia and Kivelson, 2016, Sorba et al., 2019]. We expect these local time structural asymmetries to affect the thickness of the current sheet as the structure is compressed into smaller regions or is stretched into larger regions.

A significant source of temporal variability in the current sheet thickness are the planetary period oscillations (PPOs). These have been observed in almost all magnetospheric observations (see review by Carbary and Mitchell [2013] and references therein) and are one of the key drivers of large-scale dynamics within the Saturnian magnetosphere. The resultant perturbation magnetic fields due to these current systems are quasi-uniform across the equator and quasi-dipolar in each hemisphere, closing over the respective poles. These perturbation fields affect the background magnetic field, producing both radial and meridional modulations that are

characterised by $\Phi_{N,S}$, the azimuthal position with respect to these systems. Variations in the thickness and offset of the current sheet are expected to be functions of the PPO phases, which has been observed in the tail current sheet [Provan et al., 2012, Thomsen et al., 2017, Cowley and Provan, 2017] and subsequently modelled [Arridge et al., 2011, Cowley et al., 2017, Agiwal et al., 2020].

Thickness modulations of the current sheet due to the PPOs are shown in Figure 5.3. Data in this figure was collected in 2010 when Cassini made equatorial traversals of the nightside current sheet. The top panels show plasma data from CAPS where intermittent enhancements in the plasma fluxes are observed and closely align with reversals of B_r that signify crossings of the current sheet center. These crossings occur periodically, close to the rotation rate of the planet. A key feature is the asymmetry in the north-south (slow transition) and south-north (rapid transition) crossing signatures. The ‘saw-tooth’ signature is found to be a result of PPO thickness modulations. Thomsen et al. [2017] compare this data and similar events with the PPO phases [Andrews et al., 2012, Provan et al., 2012] and models that incorporate the PPOs [Jia et al., 2012], finding good agreement. The phases and periods of these two systems have been determined for the complete Cassini mission [Andrews et al., 2008, 2012, Cowley and Provan, 2015, 2016, Gurnett et al., 2009, Gurnett et al., 2011, Kurth et al., 2007, 2008, Lamy, 2011, 2017, Provan et al., 2013, 2014, 2016, 2019b] and these can be compared with the thickness values that we determine.

In this chapter we will use the complete Cassini orbital magnetometer dataset to find when the spacecraft made fast, steep traversals of the magnetodisc current sheet, allowing us to directly determine its thickness. We aim to characterise the results in terms of the most significant sources of spatial and temporal variability within the Saturnian magnetosphere and to reveal how this current system shapes the global structure.

This work contributed to the publication of Staniland et al. [2020].

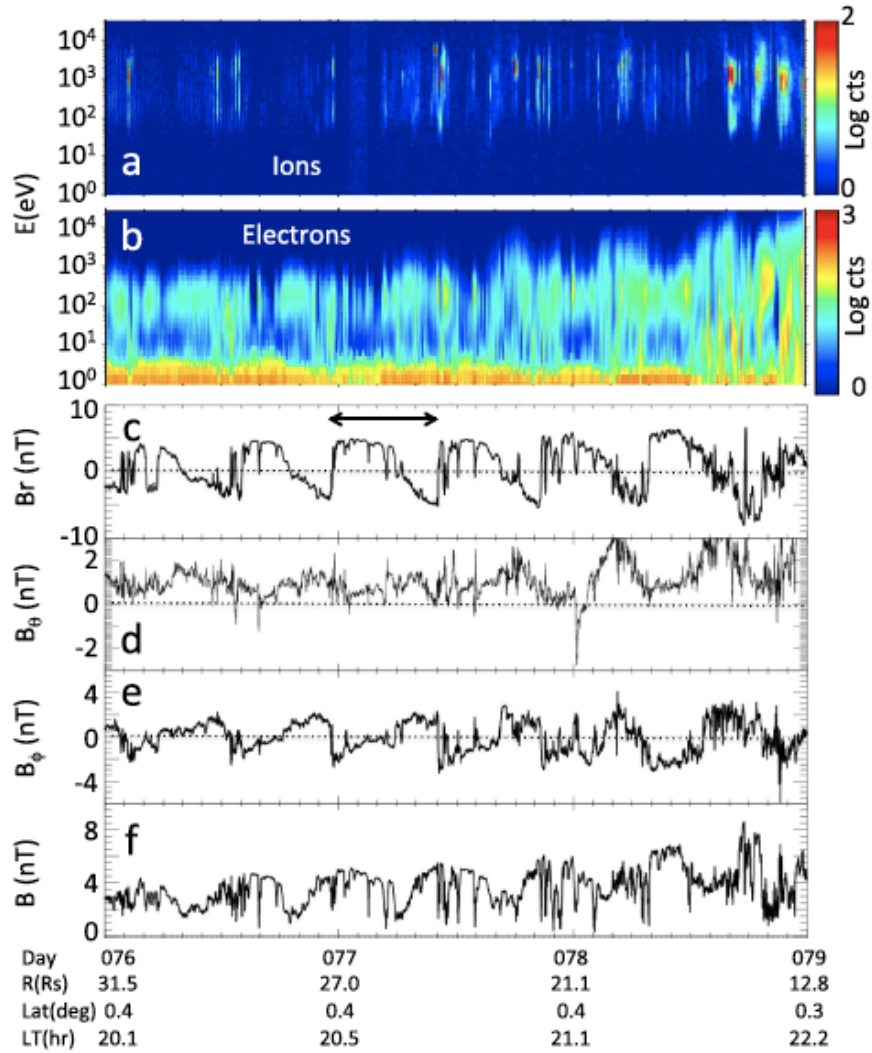


Figure 5.3: Plot from Thomsen et al. [2017] that highlights thickness modulations of the current sheet. This is shown by the asymmetric signature of B_r between north-south and south-north crossings of the current sheet, where the horizontal arrow shows the approximate rotation rate.

5.1 Data Selection

The complete Cassini orbital magnetometer dataset at 1-minute resolution is surveyed to find all crossings of the current sheet. Higher resolution

data is not required for identifying the current sheet boundaries. We work in the Kronocentric Solar Magnetic (KSMAG) coordinate system (see Section 3.3). For studying the current sheet it is best to work in cylindrical coordinates, assuming that it is not significantly warped, given by (ρ, ϕ, z) where ρ is the perpendicular distance from the z -axis and positive when pointing away from Saturn, and ϕ and z are defined in the usual way. To begin, the Cassini-11 internal magnetic field model [Dougherty et al., 2018] up to degree 4 is subtracted, since higher degree terms are unnecessary in our region of interest. To identify a current sheet crossing, we look for reversals in B_ρ and a monotonic signature during the reversal, indicating Cassini has passed through a current sheet. However, this signature alone is insufficient for identifying a crossing of the magnetodisc current sheet, and could instead be due to another current layer or some transient event that has modified the local field structure. Therefore, a set of criteria for identifying magnetodisc current sheet crossings must be defined.

Current Sheet Crossing Criteria

The plasma sourced from Enceladus which populates the magnetodisc current sheet is transported radially outwards from the moon and eventually lost down tail through plasmoid ejections, which are a consequence of either the rotationally-driven Vasyliunas cycle [e.g. Vasyliunas, 1983, Cowley et al., 2015], the solar wind-driven Dungey cycle [e.g. Dungey, 1961, Thomsen et al., 2015], or the thinning of the current sheet by the PPOs [e.g. Bradley et al., 2018]. Therefore we look for crossings that occurred at radial distances greater than $3.95 R_S$. This distance is inside the current sheet inner edge chosen in Chapter 4 which was given by Connerney et al. [1983]. Bunce et al. [2007] modelled the current sheet during the early Cassini mission and found that whilst the current sheet inner edge varied between 5 - $8 R_S$ it mostly remained close to $7 R_S$. We found that varying the inner edge of the current sheet model did not significantly improve our results

in Chapter 4 and so using a smaller value for this study does not contradict our previous results and ensures that we do not miss any current sheet crossings.

Secondly, we look for crossings close to the dipole magnetic equator, where we expect the current sheet to be situated. However, due to the seasonal tilt of the current sheet [Arridge et al., 2008a] there will be some deviation from the dipole magnetic equator. Martin and Arridge [2017] found that current sheet centre is most commonly located between $z = \pm 5 R_S$ and so we set this as our vertical range. The magnetic field strength either side of the crossing is calculated and compared with the statistical lobe magnetic field model of Jackman and Arridge [2011b] to ensure we are measuring current sheet crossings and not some other transient event that results in a reversal of B_ρ . A further cross-check with the Jackman et al. [2019] list of magnetopause crossings ensures that the event is indeed a current sheet crossing. Reversals in B_ρ can also be due to Titan flybys and are found often near current sheet crossings. These can be further identified by a reversal in B_ϕ and an enhancement in the electron density and so these events were removed from our analysis. Finally, the current sheet motion is highly dynamic, varying on yearly time-scales due to the seasonal warping and on daily time-scales due to the PPOs. Therefore Cassini needs to be travelling at a velocity near the expected motion of the current sheet. Agiwal et al. [2020] modelled the nightside current sheet, revealing the motion of the tail current sheet and its variability. From this, we define a minimum vertical speed for Cassini to be $v_z = 5 \text{ km/s}$. This removes the slowest portions of Cassini’s elliptical trajectory (i.e. apoapse).

Crossings where these criteria are fulfilled will be used to directly determine the thickness of the current sheet.

5.2 Determining the Thickness

The complete Cassini orbital magnetometer dataset at 1-minute resolution is surveyed using this set of criteria to find all suitable current sheet crossings. Two examples of these are shown in Figure 5.4. For each example, there is a B_ρ reversal, shown in panels a) and f) of Figure 5.4, implying the centre of the current sheet has been crossed, with an approximately linear variation in B_ρ as Cassini cuts through the layer of plasma. B_ρ then either remains constant or reduces with height from the current sheet as the field becomes less radially distended. In panels b) and g) of Figure 5.4, B_z remains approximately constant due to the zero divergence of the magnetic field. Hence the boundaries of the current sheet are determined from the signature of B_ρ alone and are shown for the two examples in Figure 5.4 with dashed vertical lines.

We use a new data-driven method for identifying the current sheet boundaries by analysing the variation in the magnetic field structure due to the current sheet. We begin by calculating the variance of B_ρ in a 1-hour sliding window. When B_ρ is steady, the variance is approximately zero. When B_ρ is highly variable, for instance during a current sheet crossing, there is a significant increase in the variance and so we can use the beginning and end of this increase to identify the boundaries of the current sheet. Based on visual inspection of the data, we define a minimum threshold for this increase to be when the variance is greater than or equal to 0.4 nT^2 . Marginally varying this threshold does not significantly alter the chosen location since we are looking for a sudden increase in the variance, so we essentially need to set the limit to be when the variance is not approximately zero. However, based on visual inspection this value was found to best identify the boundaries for all of the events, including those where the spike in the variance was less pronounced. Panels a) and f) in Figure 5.4 show that this threshold provides a good estimate for identifying the current sheet boundaries.

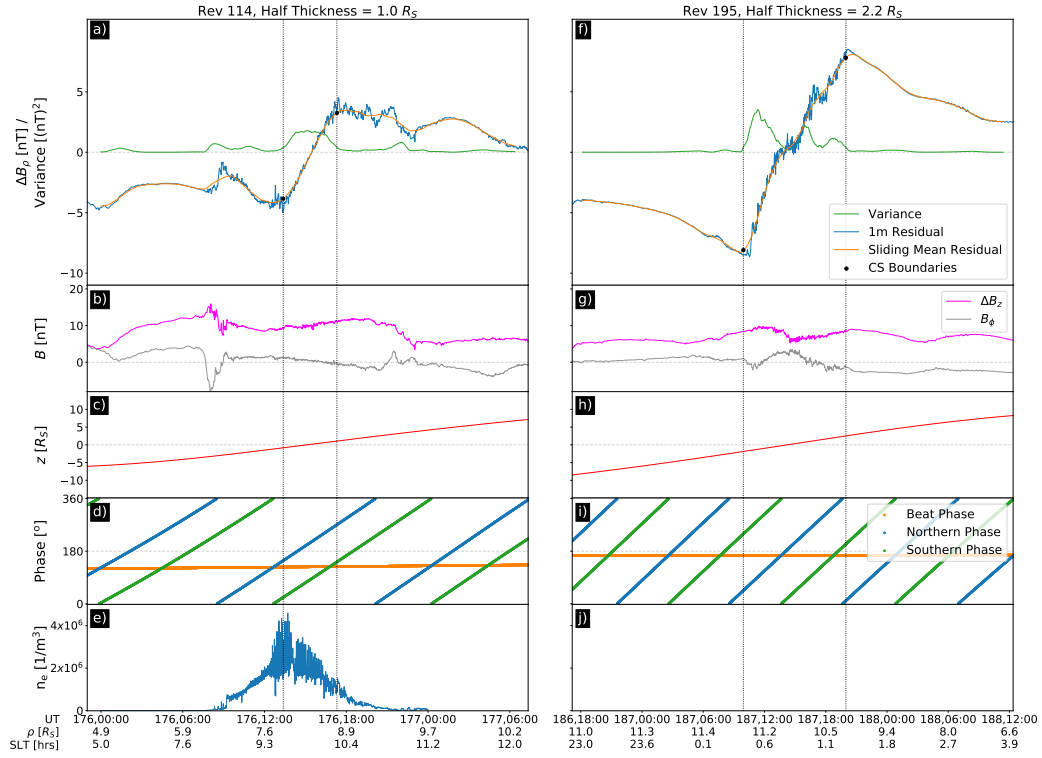


Figure 5.4: Residual magnetic field data, having subtracted the Dougherty et al. [2018] internal field model, for Rev 114 in 2009 is shown on the left and Rev 195 in 2013 is shown on the right, both as a functions of time. Note that the plotted range of time for Rev 195 is longer than for Rev 114. Panels a) and f) show ΔB_ρ at 1-minute resolution in blue, with a 2-hour sliding mean shown in orange. The green line shows the variance calculated in the sliding window. A clear spike identifies the current sheet (CS) crossing, with the boundaries shown by the dashed lines. Panels b) and g) show ΔB_z and B_ϕ , both of which lack a clear signature of the current sheet boundaries. Panels c) and h) show Cassini's distance from the equator in KSMAG coordinates. Panels d) and i) show the northern, southern and beat phases of the PPOs in blue, green and orange, respectively. Both cases are in near-antiphase conditions. Panel e shows the bulk thermal electron density determined using the CAPS ELS instrument for Rev 114. Panel j is empty because CAPS was turned off in 2012. At the bottom of the figure the day of year and time, the perpendicular distance of Cassini from the dipole axis, and Cassini's local time position in decimal hours are shown. Figure taken from Staniland et al. [2020].

For some cases, such as Rev 195 in Figure 5.4, there are multiple spikes in the variance during a crossing due to the B_ρ signature between the two boundaries not being perfectly linear. To account for this, we assume that if variance falls below 0.4 nT^2 for only a short period (chosen to be less than 45 minutes based on testing different values on our set of events), or if the field magnitude is less than half the value of the field magnitude at the first boundary (assuming the field will be of a similar magnitude either side of the current sheet) Cassini is determined to still be within the current sheet. The reduction in the variance below the threshold is therefore not due to the spacecraft passing through the boundary. Nonetheless, the location of the current sheet boundary could not always be identified by this method because of the variability in B_ρ most likely due to a faster current sheet motion in these instances. These events were discarded so that only events with a clear signature were used.

This variance analysis is performed multiple times whilst increasing the sliding window size until the results converge within 2σ of the average position. The z position of Cassini in KSMAG coordinates at the current sheet boundaries is given by z_1 and z_2 and these are used to determine its structure. The half-thickness of the current sheet is given by $|z_2 - z_1|/2$ and the offset of the current sheet centre is given by $(z_2 + z_1)/2$, assuming the current sheet is not significantly warped.

We show two example orbits where we have used the method outlined herein to determine the current sheet thickness in Figure 5.4. For Rev 114, shown in the left panels of Figure 5.4, the half-thickness of the current sheet was $1.0 R_S$ and the offset of the centre was $0.1 R_S$. This crossing occurred at $\sim 8 R_S$ on the dayside, around 10am local time and took approximately ~ 4 hrs to pass through the current sheet. In this case the current sheet was particularly thin and close to the equator. The current sheet is expected to be almost co-located with the rotational equator since it occurred in 2009, close to equinox. For Rev 195, shown in the right panels of Figure 5.4, the

half-thickness was $2.2 R_S$ and the offset was $0.3 R_S$. Since this crossing occurred in 2013 during northern summer, the positive offset is unexpected. The orbits that preceded this example were checked and whilst they occurred at almost identical radial distances and local times, the offset, as well as the thickness, was not the same in each case, showing evidence of temporal variability. For Rev 195, Cassini took approximately ~ 10 hours to traverse the current sheet, almost the length of a PPO cycle, which could imply that the current sheet has moved whilst Cassini passes through. We chose not to set an upper limit on the time taken for a crossing because this would limit the maximum thickness that can be directly measured and so we include all examples that fulfilled the criteria we have set out.

Panel e) of Figure 5.4 shows the electron density Lewis et al. [2008] determined using counts from the CAPS Electron Spectrometer [Young et al., 2004]. For Rev 114 the plasma sheet appears to be asymmetric about the current sheet centre, where the peak central sheet thermal electron density is $\sim 3 \times 10^6 \text{ m}^{-3}$. Whether this asymmetry is temporal or spatial is difficult to determine using in-situ data. For instance, the plasma sheet could be moving southward as Cassini is passing through it. For Rev 195, there was no data collected because the instrument was turned off in 2012, hence why panel j) in Figure 1 is empty. Sergis et al. [2011] compared the properties of the current and plasma sheets, showing that these two systems can behave independently. In some cases they observed an increase in the current sheet thickness but not the plasma sheet, with the peak plasma sheet density and pressure remaining the same.

We have identified 66 crossings of the magnetodisc current sheet where we can use this method to determine its thickness. Whilst there were additional current sheet crossings throughout the Cassini mission, these were not used in this study. For instance, during the 20 F-ring orbits Cassini crossed the nightside current sheet and these events were analysed by Agiwal et al. [2020]. The slow movement of Cassini coupled with the fast mo-

tion of the current sheet means that the magnetic field signature during a crossing was not a simple reversal in B_ρ and instead was highly variable, indicating current sheet flapping. These were excluded from our analysis.

The location of each current sheet crossing we have identified are shown in Figure 5.5. The left panel shows the local time distribution, where the crosses show the location of the current sheet centre for each event. The v_z constraint prevents us from using the data at dawn and dusk because Cassini was either moving too slowly, was at the equator when it encountered the current sheet, or Cassini made a fast steep crossing of the equator within the inner edge of the orbit of Enceladus. Therefore, our analysis of the thickness is restricted to the near-noon and near-midnight sectors. The right panel of Figure 5.5 plots the latitudinal distribution of the crossings, showing that they all occur close to the equator, well within our $\pm 5R_S$ boundary, and appear to be well separated by season. However, there is some variability in the location of the current sheet centre. In Figure 5.5, the dashed black lines show the trajectory of Cassini 12 hours either side of the current sheet boundaries for each crossing. We can clearly see that for each event Cassini made a fast, steep traversal through the equatorial region, allowing for a direct determination of the current sheet properties.

Model-based Approach

The other approach for determining the current sheet boundaries is by using a model, such as the CAN model [Connerney et al., 1983]. However this can be slow due to the model formulae being integrals over Bessel functions that must be evaluated numerically. In addition, we are not aiming to give a complete description of the current sheet, nor are we aiming to test the validity of any models. For determining the current sheet boundaries, a data-driven approach using this simple variance analysis of the B_ρ signature is suitable and efficient. Nonetheless, an additional cross-check of our results was performed by using the Edwards et al. [2001] analytic approx-

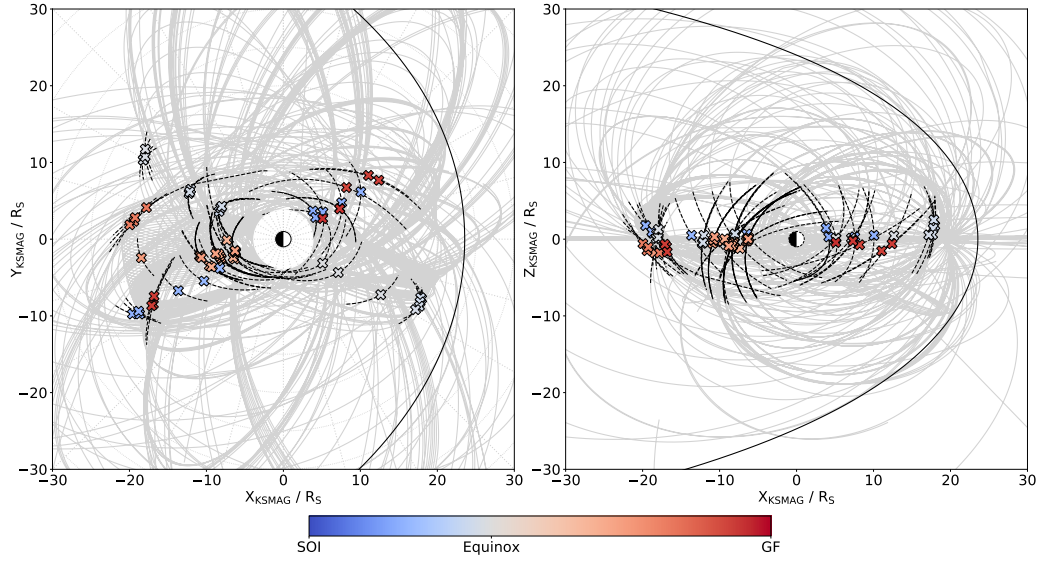


Figure 5.5: The complete Cassini mission trajectory is shown in light grey with a dawn-dusk asymmetric magnetopause [Pilkington et al., 2015a] for a solar wind dynamic pressure of 0.01 nPa shown in black, projected onto the equatorial plane in the left panel and onto the meridional plane in the right panel. The dashed black lines show the trajectory of Cassini 12 hours either side of the current sheet boundaries during each of our 66 events. The crosses show the location of the current sheet centre during each crossing, and are colour-coded by time. Figure taken from Staniland et al. [2020].

imations of the CAN model. We fix the current sheet inner edge at $3.95R_S$ and outer edge at $30R_S$ and use the boundaries identified with the above variance analysis as an initial condition and to set upper and lower bounds for the current sheet thickness and offset. We then use a non-linear least squares procedure to fit the Edwards et al. [2001] model approximation to the magnetic field data to find the current sheet thickness, offset and $\mu_0 I_0$ current intensity for each pass. We present two examples of this in Figures 5.6 and 5.7.

In Figure 5.6 we compare the current sheet thickness determined using the two different techniques for Rev 195. We see that both methods picked

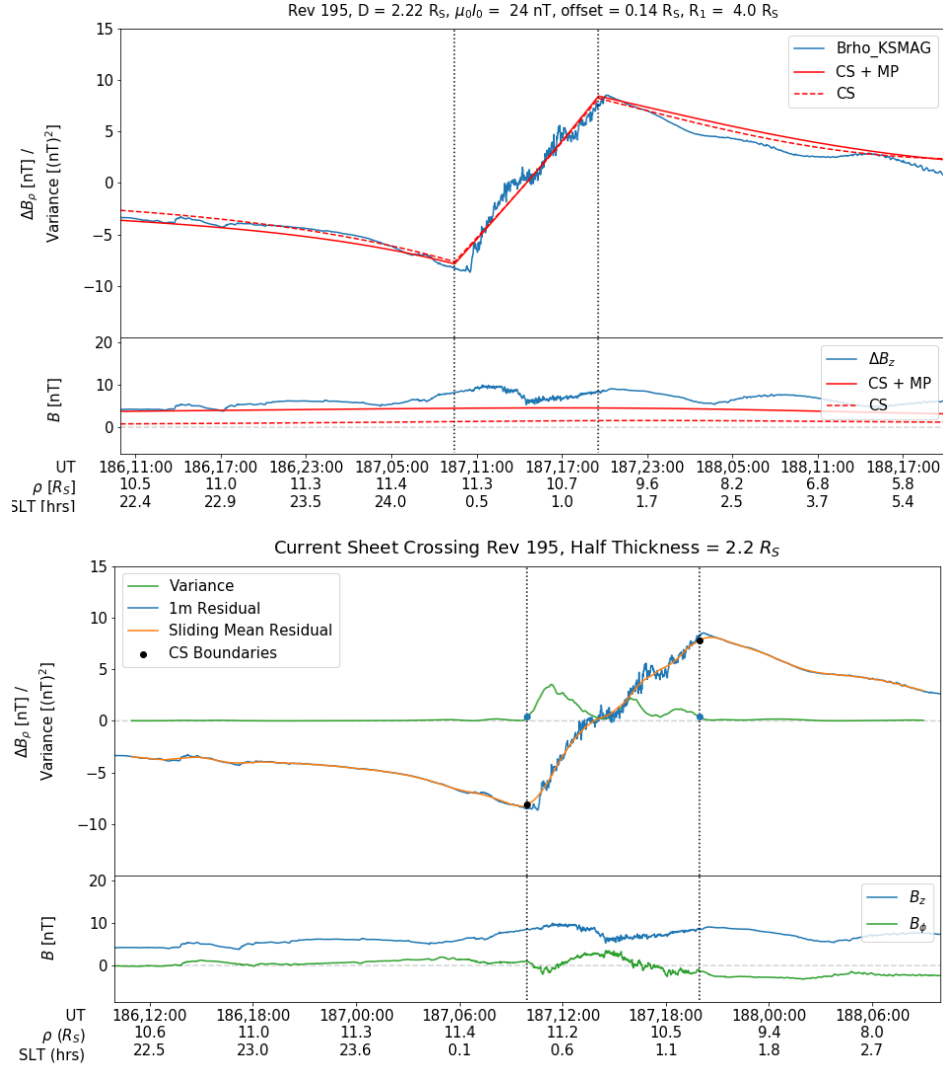


Figure 5.6: Comparing the current sheet boundary identification methods for Rev 195 through the midnight current sheet, using the Connerney et al. [1983] current sheet model (top) and our approach based on the variance of the field (bottom). This is a clear example of both methods providing the same result, primarily due to the very distinct boundary signatures with a steady field either side of the current sheet and approximately linear slope through the current sheet.

out almost identical positions for the current sheet boundaries and both determined a thickness value is $2.2R_S$. This is unsurprising considering the method outlined here was constructed to identify the same field signature as the model, and for this example there is a clear reversal in B_ρ with defined upper and lower boundaries for the current sheet. Note for the left panels we have also included an approximation for the magnetopause and tail current systems, however this was not fit to the data, hence why the B_z -component is underestimated by the model. We are not trying to give a full description here for the strength of all these current systems and instead solely focus on the current sheet boundaries identified purely for in B_ρ .

In Figure 5.7 we compare the current sheet thickness determined using the two different techniques for Rev 109. This is an example where the two methods give us different values for the current sheet. The model estimated a thickness of $0.7R_S$ whilst the variance analysis estimated a thickness of $1.4R_S$. We can see from this case study that this particular example has a far less obvious current sheet crossing signature compared to Rev 195 in Figure 5.7. Current sheet flapping could produce the observed B_ρ signature. For this example, the model gives a better approximation.

Nonetheless, the modelling approach requires initial conditions for the fitting procedure to then iterate from. Considering these initial guesses are taken from our original variance method, it seems unnecessary to then perform a fit unless the results are significantly better. Overall, we found that using the model did not impact our main results. We found the same median half-thickness value and day-night asymmetry that will be discussed in Section 4. Therefore, we choose to use the results from our variance method.

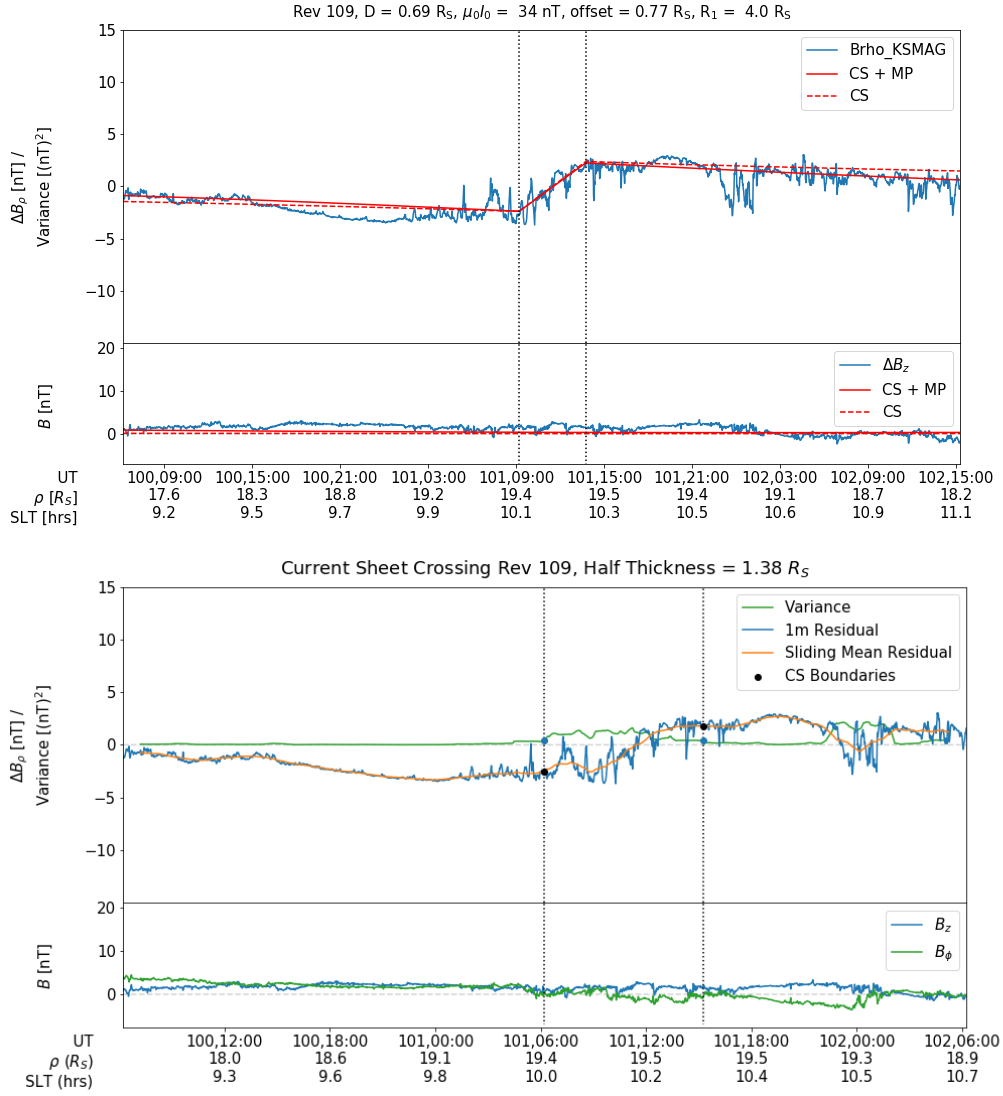


Figure 5.7: The same as Figure 5.6 but for Rev 109 through the dayside current sheet. For this example we can see that the crossing signature is not as clear as Rev 195. The data is far noisier, making the detection of the boundaries using the variance analysis more difficult, resulting in a thicker current sheet compared to the CAN model approach.

Minimum Variance Analysis

An assumption of our approach is that the current sheet thickness should be measured parallel to the dipole axis. However, if the current sheet is

warped out of the equator, for instance due to the seasonal displacement of the current sheet [Arridge et al., 2008a], the current sheet normal will not be parallel to the z -axis. To test how our measurements would be altered by including this offset, we use Minimum Variance Analysis (MVA) to determine the current sheet normal [Sonnerup and Scheible, 1998]. Assuming the current sheet is a 1D thin tangential discontinuity (i.e. the current sheet parameters only vary in the normal direction) which is not time dependent, the divergence of the magnetic field through the current sheet should be zero and so its normal should have a fixed direction. Hence, the direction of minimum variance during a current sheet crossing should be equivalent to the current sheet normal.

To perform MVA, a two hour sliding average of the magnetic field during a current sheet crossing and two hours either side is taken. We create an array of the magnetic field vectors measured and find the covariance matrix of the three field components during a current sheet crossing. We then determine the eigenvalues (λ_i for $i=1,2,3$) and eigenvectors ($\mathbf{x}_i$ for $i = 1,2,3$) of the covariance matrix. Since the covariance matrix is symmetric λ_i are all real and $\mathbf{x}_i$ are orthogonal. Hence, $\mathbf{x}_i$ tell us the direction of maximum, intermediate and minimum variance of the field for $i = 1,2,3$, respectively. The eigenvalues λ_i represent the absolute variance and comparing their magnitudes reveals how well the normal can be constrained. The current sheet normal is equivalent to the minimum variance vector. Once the normal has been calculated, taking the dot product of it with the assumed current sheet normal, perpendicular to the equator, gives us the angular offset and reveals the tilt of the current sheet.

Estimates for the standard deviation of the current sheet normal are found using the bootstrapping method [Kawano and Higuchi, 1995]. We perform MVA multiple times using bootstrap samples, where we select a sample of vectors with replacement until we have a sample that is the same size as the current sheet traversal dataset we are considering. We perform

MVA 10,000 times using the bootstrap samples to calculate 10,000 current sheet normal vectors. The mean current sheet tilt and its standard deviation can be found using these vectors. An example is shown in Figure 5.8 for Rev 43, where we find the average tilt between the current sheet normal and the vector parallel to the z -axis is -9° with a standard deviation of 1° . Here the negative sign implies the current sheet normal points more towards the planet (i.e. southern summer where the solar wind forces the current sheet northwards).

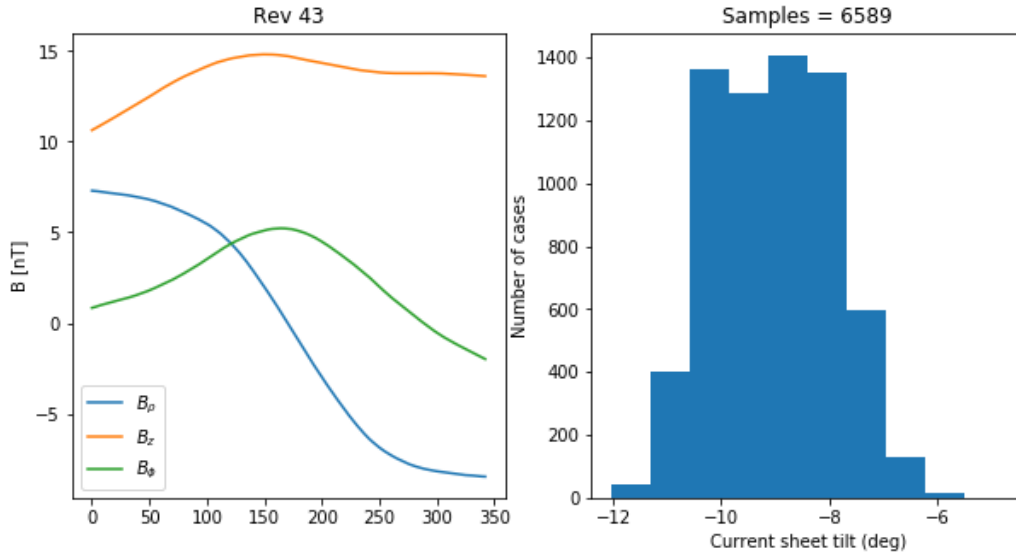


Figure 5.8: The left panel shows the 2-hour sliding average of the magnetic field components during the Rev 43 (March 2007) current sheet crossing as a function of time. We see a reversal in B_ρ but also observe variability in the other magnetic field components. We use the bootstrap method to calculate 10,000 current sheet normals and the results are shown on the right. We see that only 6589 normal vectors could be calculated due to the eigenvalue ratio threshold we have set. The mean tilt is -9° implying the current sheet normal is pointing more towards the planet, indicative of solar wind warping of the current sheet during southern summer.

However, MVA cannot always conclusively determine the normal. For instance, if there is variability in B_z of a similar order of magnitude to the

variability in B_ϕ MVA cannot distinguish between the direction of minimum and intermediate variance. This degeneracy can be determined by comparing the magnitudes of λ_i as these tell us the relative variance in each direction. We use the common threshold of $\lambda_2/\lambda_3 > 10$ to signify a good determination of the current sheet normal. If $\lambda_2/\lambda_3 < 10$ the covariance matrix is nearly degenerate and so we use the Coplanarity Method instead. This calculates the normal by finding $\Delta B \times (B_N \times B_S)$, where B_N and B_S are the mean magnetic field calculated at the northern and southern current sheet boundaries, so taking their cross product gives a vector tangential to the sheet, ΔB is the difference between these two vectors and is in the plane of the sheet. Therefore the cross product of these will give a vector perpendicular to the current sheet [Martin and Arridge, 2017]. Knowing the standard deviation of the mean vectors B_N and B_S , we use error propagation to determine the standard deviation of the normal vector calculated using the Coplanarity Method. When these are smaller than the MVA bootstrap errors, or the MVA eigenvalue analysis was degenerate, the Coplanarity Method is used instead.

The results are shown in the left panel of Figure 5.9, where a negative offset implies the field is bent northward and a positive offset implies the field is bent southward. We see that the current sheet normal is most often found to be almost aligned with the assumed normal, where the maximum displacement was $\pm 40^\circ$. To see how this reduces the half-thickness, we multiply our calculated half-thickness values by $\sin \theta$ where θ is the change in angle. These results are shown in the right panel of Figure 5.9. The change in angle is mostly well organised by season, however there is some variability, revealing the dynamic structure of the current sheet. The average decrease in half-thickness is $0.1R_S$ with a maximum decrease of $0.5R_S$, but there were only three cases where the decrease was this large, with most of the changes clustered around $-0.1R_S$. This implies that there is only a minor change in the thickness if the current sheet normal is not

assumed to be perpendicular to the rotational equator. However, we must consider the errors associated with MVA and the Coplanarity Method. For some cases the errors were too large to make the calculated normal trustworthy, most commonly due to the time taken for a crossing. In addition, whilst we expect this to be one of the most significant sources of error, there are other potential sources that we have not considered. Therefore, we define an approximate order of magnitude error in the calculated half-thickness for all our crossings to be $\pm 0.1 R_S$.

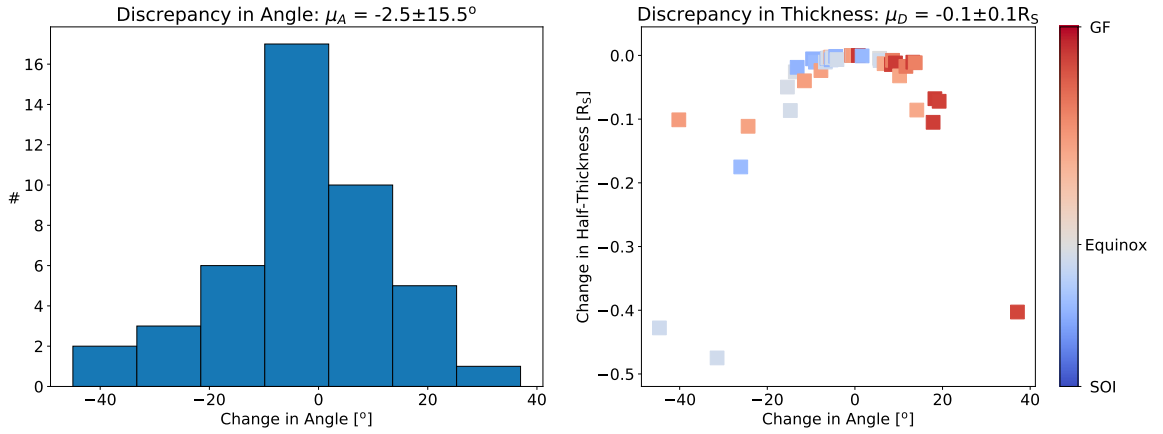


Figure 5.9: The discrepancy between the assumed current sheet normal, parallel to the dipole axis, and the calculated normal from the magnetic field data, due to the tilt of the current sheet. The left panel shows a histogram of the angular offsets, where the normal was calculated either using Minimum Variance Analysis (MVA) or the Coplanarity Method, depending on which technique had the smallest associated errors. The plot title shows the mean tilt of the current sheet, μ_A , and one standard deviation in degrees. In the right panel, the change in thickness is plotted with respect to the associated angular discrepancies, where the colour represents the time of crossing, ranging between Saturn Orbital Insertion (SOI) in July 2004 and Cassini’s end of mission phase, known as the Grand Finale (GF), in September 2017. The colour bar changes from blue to red at Saturn’s Equinox in August 2009. The plot title shows the mean change in thickness, μ_D , and one standard deviation in units of R_S . Figure taken from Staniland et al. [2020].

5.3 Results

We have a catalogue of 66 current sheet crossings that have significant spatial and temporal coverage. We find that the median current sheet half-thickness is $1.3R_S$, thinner than the initial calculations for the half-thickness from early flybys of $2.5R_S$ [Connerney et al., 1981b, Bunce and Cowley, 2003, Giampieri and Dougherty, 2004], but within the range of values calculated by Kellett et al. [2009]. The interquartile range of this dataset is $1R_S$ and skewed towards smaller values, implying that the current sheet thickness is highly variable and more often thinner than the median. The thinnest value found was $0.4R_S$ and the thickest value was $3.2R_S$, both of which were observed on the nightside, revealing the nightside current sheet to be highly variable. The range of values is greater than that calculated by Kellett et al. [2009], predominantly reflecting our larger dataset that covers more of the Saturnian system. For instance, our thinnest value is found at $\rho = 21R_S$ on the nightside, a distance outside the presumed outer edge of the current sheet by Kellett et al. [2009]. Modelling of the tail current sheet using equatorial data has found even larger half-thickness values $> 10R_S$ at greater radial distances [Arridge et al., 2011, Martin and Arridge, 2017]. The v_z constraint limits us from using data at these radial distances because Cassini was at the slowest point of its orbit. The current sheet would pass through the slowly moving spacecraft and so the change in Cassini's z -position between each boundary would be small, giving an underestimate of the thickness. The v_z threshold is predominantly satisfied when ρ is less than $25R_S$ and so we focus on data within this radial distance.

5.3.1 Spatial Variability

To test whether there is a thickness spatial dependency, the data is separated into dayside and nightside local time sectors, and binned into two ra-

dial ranges - the quasi-dipolar region ($< 15R_S$) and the magnetodisc proper ($\geq 15R_S$). This is shown in Figure 5.10, revealing both a day-night thickness asymmetry and a radial dependence.

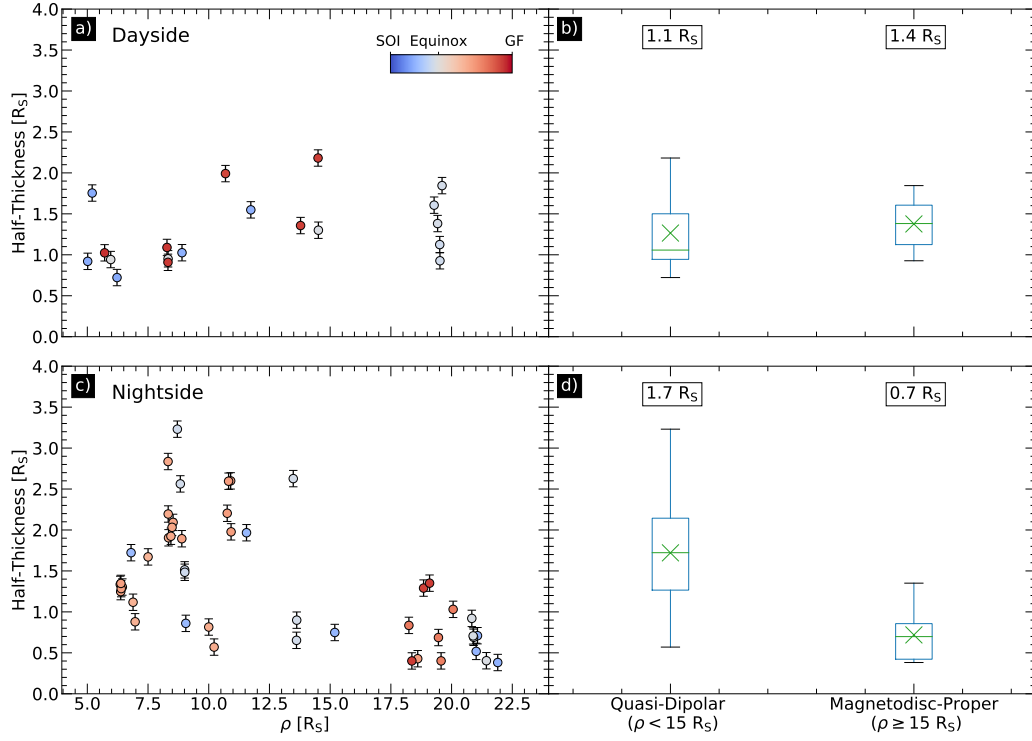


Figure 5.10: The top two panels show the half-thickness calculated for all dayside magnetodisc current sheet crossing events, whilst the bottom two panels are for the nightside events. Panels a) and c) plots the half-thickness as a function of radial distance, colour coded by season. Panels b) and d) are box plots of the half-thickness binned into the two radial regions, showing the median, interquartile ranges, maximum and minimum values and the mean is also shown by the green cross. The values at the top of panels b) and d) show the median current sheet thickness in each region, in units of R_S . Figure taken from Staniland et al. [2020].

Panels a) and b) in Figure 5.10 show the thickness of the 19 dayside events as a function of their perpendicular distance from the spin axis, ρ . The median dayside half-thickness is $1.1R_S$, marginally thinner than the

global average, but with an interquartile range of $0.6R_S$, revealing some variability about this average value. In panel b), where the data has been binned into the two radial ranges, the current sheet appears to get slightly thicker with radial distance, from $1.1^{+0.4}_{-0.1}R_S$ to $1.4^{+0.2}_{-0.3}R_S$. However we see that these are within errors of each other, where the interquartile ranges of the two box plots overlap. Considering that the magnetodisc proper only contains 4 data points, it is difficult to claim this is a real radial profile. What we do observe is that the thickness remains within a small range of values on the dayside, implying that the current sheet thickness is not highly variable. On average the current sheet remains approximately constant with radial distance. This could be reflective of the dayside magnetosphere being compressed by the solar wind, preventing the magnetodisc geometry from forming and the current sheet from becoming thinner. When the field becomes more radially distended, the highly stretched field concentrates the plasma towards the equator and thins the current sheet. When the dayside magnetosphere is more expanded, due to either low solar wind dynamic pressure [Arridge et al., 2008b] or an increase in the internal plasma pressure [Pilkington et al., 2015a], the current sheet would be thinner as the field becomes more radial.

Panels c) and d) of Figure 5.10 show the thickness of the nightside current sheet. Panel a) shows the thickness during all 47 available crossings as a function of ρ whilst panel d) shows the data binned into the two radial ranges. The median nightside half-thickness is $1.3R_S$, slightly thicker than the dayside but with a larger interquartile range of $1.2R_S$ revealing the nightside current sheet thickness to be highly variable. Unlike the dayside, there appears to be a radial trend. In the quasi-dipolar region, the average, or nominal, current sheet half-thickness is $1.7^{+0.4}_{-0.5}R_S$ and so the spread of values is not significantly skewed either side of the median. The average nightside current sheet is 50% thicker than the dayside and so whilst there is marginal overlap between the interquartile ranges of the dayside and

nightside quasi-dipolar data we shall explore what could physically produce this feature.

The presence of some other observed day-night asymmetries within the Saturnian magnetosphere have been linked to the noon-midnight electric field in the inner magnetosphere (see review by Thomsen et al. [2012] and references therein). The associated convection pattern with this electric field implies that particles drift outwards at dawn and inwards at dusk. These drifts can be seen in Figure 5.11. The drift pattern would result in adiabatic heating of the plasma on the nightside and cooling on the dayside. Observations have identified differences in W^+ temperature between the dayside and nightside of $\sim 10 - 100$ eV for $r < 15R_S$ [Thomsen et al., 2012, Wilson et al., 2017]. The higher nightside temperature would imply a larger centrifugal scale height of the current sheet, and so we might expect a thicker current sheet on the nightside compared to the dayside in the quasi-dipolar region as a result of these particle drifts. Why this convection pattern exists is still not completely understood [Wilson et al., 2017], but this convection pattern has been reproduced by the simulations of Jia and Kivelson [2016], who suggest it is the result of the confinement of the field and plasma at noon and dusk compared to the expansion at midnight and dawn. Nonetheless, our results appear to provide further support for the presence of a noon-midnight electric field at Saturn.

Simulations of the Saturnian magnetosphere by Jia and Kivelson [2016] found a local time asymmetry in the magnetodisc. They identified a thicker current sheet in the middle magnetosphere ($9 - 15R_S$) at dusk compared to dawn, due to the dipolarization of the field as a response to its confinement by the magnetopause, which is closer to the planet at dusk compared to dawn [Pilkington et al., 2015b]. They found that the plasma does not return to the equator as the flux tubes corotate through the afternoon sector and so this feature could continue through to the nightside, resulting in a thicker current sheet close to the planet. However, on the nightside the field is no

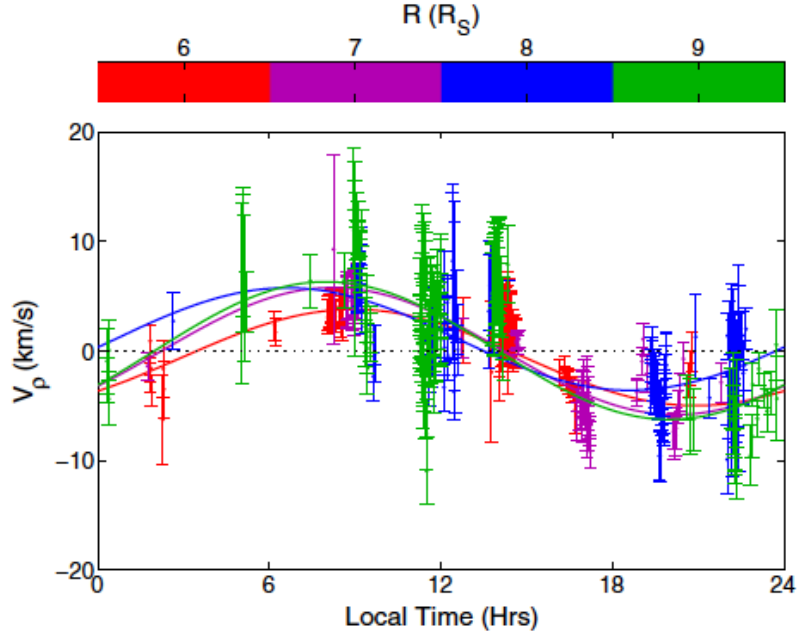


Figure 5.11: Figure from Wilson et al. [2013] showing the radial velocity of thermal plasma (OH^+ and H^+) in the inner magnetosphere of Saturn that was calculated using CAPS data as a function of local time. We see the plasma moves outwards near dawn and inwards near dusk producing an electric field that is directed from noon to midnight, although slightly offset.

longer confined and is able to stretch down tail. Figure 5.10 shows that the current sheet thins with radial distance on the nightside, revealing the field curvature to be much higher. The sheet reduces in thickness with radial distance by more than a half from an average half-thickness of $1.7^{+0.4}_{-0.5} R_S$ to $0.7^{+0.2}_{-0.3} R_S$, with far less variability in the outer region and no overlap between the errors associated with each radial range. This suggests it is a true radial profile of the current sheet thickness on the nightside.

This observed day-night asymmetry in current sheet thickness could also be reflective of the inherent difference in field geometry at similar radial distances on the nightside and dayside. If we consider the distance

between the equator and magnetopause at a given radial distance, it will be larger on the nightside than the dayside due to the polar flattening of the magnetopause. In the right panel of Figure 5.5, at $x = 10R_S$ on the dayside, the magnetopause boundary is at approximately $z = 20R_S$. But on the nightside at $x = -10R_S$ the boundary is at $z = 30R_S$. The magnetic field is less confined, which could allow the plasma to expand further along the field lines, increasing the current sheet thickness.

5.3.2 Temporal Variability

A difficulty in using in-situ measurements is separating spatial and temporal variability. We must consider whether the spatial day-night asymmetry is a result of a temporal observation bias. The PPOs are ubiquitous within the Saturnian magnetosphere and so we consider the effect these might have on our dataset. When the PPO systems are in-phase, the thickness modulations are expected to be smaller compared to when they are in antiphase. If the dayside was measured more frequently during in-phase conditions compared to the nightside, this could explain the observed asymmetry. To test this, during each crossing we look at $\Phi_{N,S}$, the global phases of the PPOs that have been determined for the complete Cassini mission [Andrews et al., 2008, 2012, Cowley and Provan, 2015, 2016, Gurnett et al., 2009, Gurnett et al., 2011, Kurth et al., 2007, 2008, Lamy, 2011, 2017, Provan et al., 2013, 2014, 2016, 2019b]. We firstly transform the global phases $\Phi_{N,S}$ into a local phases, to account for both Cassini's position in local time and a $3^\circ R_S^{-1}$ radial phase delay that is expected when Cassini is outside of the core PPO region, at distances $\rho > 12R_S$ [Arridge et al., 2011, Provan et al., 2012]. The local PPO phases are then given by

$$\Psi_{N,S}^* = \Phi_{N,S} - \phi - G[r - 12], \quad (5.1)$$

where ϕ is Cassini's azimuthal position and G is the radial phase gradient.

The relative phase of the PPOs, or beat phase, at Cassini's location is given by $\Delta\Psi^* = \Psi_N^* - \Psi_S^*$. The variation in beat phase during a single crossing is small and so we use the beat phase calculated at the current sheet centre for each crossing. The events within the dayside and nightside quasi-dipolar region are separated by their beat phase. When $\Delta\Psi^* = 0 \pm 90^\circ$ the PPOs are in-phase, and when $\Delta\Psi^* = 180 \pm 90^\circ$ they are in antiphase. Each bin will therefore contain crossings that occurred when the PPO current systems were in quadrature ($\Delta\Psi^* \approx 90^\circ$ and $\Delta\Psi^* \approx 270^\circ$). Nonetheless, even with this wider range we would still expect to see the largest thickness modulations to occur during antiphase conditions.

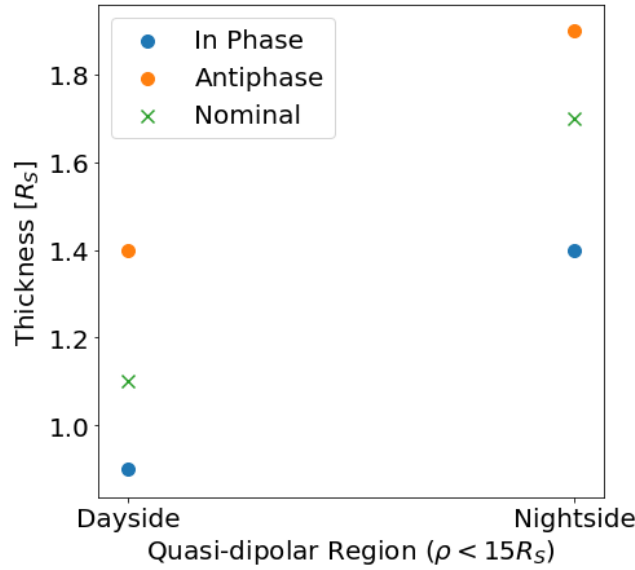


Figure 5.12: The average dayside and nightside current sheet thickness is shown for in phase and antiphase PPO conditions alongside the averages determined in Figure 5.10.

The results are shown in Figure 5.12. We find that both the nightside and dayside current sheet are slightly thicker than the average value shown in Figure 5.9 in the quasi-dipolar region during antiphase conditions. The median dayside current sheet half-thickness is $1.4^{+0.5}_{-0.2} R_S$ and the nightside

is $1.9 \pm 0.5 R_S$, showing an increase of 30% and 10%, respectively, although we note that there is some overlap between their associated errors. Hence we see a greater difference for the dayside, yet still observe on average a thinner current sheet compared to the nightside. During in-phase conditions, the average dayside half-thickness decreases to $1.1 R_S$, with negligible error bars due to only having a few data points, and the average nightside half-thickness decreases to $1.4^{+0.5}_{-0.2} R_S$, both reducing on average by 20%. Whilst there appears to be a beat phase thickness dependence, they have a similar effect for both local time sectors. This suggests that the day-night thickness asymmetry is not due to a PPO beat phase observation bias.

To determine whether there is a thickness seasonal dependence, Figure 5.10 also shows the time of Saturn's year for each crossing. The results do not appear to have any clear ordering with respect to time. If the current sheet was thinnest close to equinox, we would expect to see the light blue and red points below the darker blue and red points. Whilst we observe variability in the thickness shown in Figure 5.10 there is no clear preference for a thicker or thinner current sheet during a specific period of the Saturnian year. Our results do not provide any clear evidence for a thickness seasonal dependence. In Figure 5.13 we show the offset as a function of time. Here we observe a clear seasonal dependence that is due to the seasonal warping of the current sheet by the solar wind Arridge et al. [2008a].

Whilst we have considered how well the thickness modulations are ordered by the beat phase of the PPOs, we now consider the northern and southern PPO phases during each crossing. We separate the data into each local time and radial bin during both in-phase and antiphase conditions to look for a PPO dependence. When $\Psi_S^* = 0^\circ$ and $\Psi_N^* = 180^\circ$ the meridional component of the perturbation magnetic field produced by the PPOs adds to the southward directed background field and subtracts from it when $\Psi_S^* = 180^\circ$ and $\Psi_N^* = 0^\circ$. We therefore expect the current sheet to be

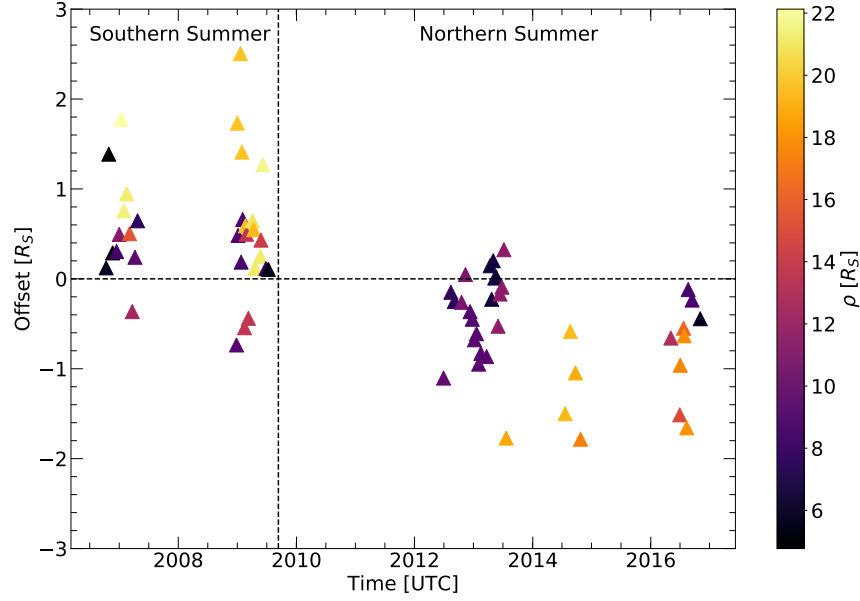


Figure 5.13: The offset of the current sheet is shown as a function of time and colour-coded based on perpendicular radial distance from the spin axis. We see that current sheet is predominantly warped northwards before equinox due to the solar wind warping the current sheet during southern summer. The opposite effect is observed post-equinox for similar reasons. Some of the variability could be due to both distance from the planet during the current sheet crossing as well as the PPOs that modulate the current sheet offset.

thicker when $\Psi_S^* = 0^\circ$ and $\Psi_N^* = 180^\circ$ since the equatorial field strength has increased, and thinner in the opposite case [see Figure 2 in Cowley and Provan, 2017]. When the two current systems are in-phase we would expect the thickness modulations due to each current system to approximately cancel, whereas when the systems are in antiphase we would expect the thickness modulations to add.

We begin by looking at the PPO phases during each crossing. Since the time taken for Cassini to traverse the current sheet varies between 3-18 hours for our set of events, the northern and southern phases will vary during a crossing. Hence, for each event we calculate the directional mean

[Mardia and Jupp, 2009] $\langle \Psi^* \rangle$ given by

$$\frac{1}{K} \sum_{K=1}^K e^{i\Psi_K^*} = R e^{i\langle \Psi^* \rangle}, \quad (5.2)$$

where K is the number of data points, R is the mean resultant length of the data and the circular standard deviation is given by

$$\sigma = \sqrt{\ln(R^{-2})}. \quad (5.3)$$

The mean value tells us the average phase during a crossing and the standard deviation represents the range of phases during a crossing. If the standard deviation is large, Cassini spent a significant period of time within the current sheet. We remove the 12 events that took longer than an approximate PPO cycle (~ 11 hrs) from this part of the analysis, leaving us with 54 events.

Figures 5.14a) and b) plot the thickness and offset, respectively, as a function of Ψ_S^* for crossings that occurred in the nightside magnetodisc proper region. There are 14 events that occurred between 2007 and 2016. Panels c) and d) of Figure 5.14 show data from the quasi-dipolar region. There are 25 events that occurred between 2007 and 2013. A sine curve was fit to the data to determine whether the variability in thickness is well described by the expected PPO modulations from both the northern and southern phases. The amplitude, phase offset, and central value were free parameters, which reveal the magnitude of the PPO modulation, a phase delay, and the unperturbed half-thickness, respectively. The horizontal error bars show the circular standard deviation. The vertical error bars show the error associated with determining the thickness. The $\pm 0.1 R_S$ error approximation is also applied to the measured current sheet offset.

Figure 5.14a) shows that the thickness modulations in the magnetotail appear to be reasonably organised by the southern PPO phase. The fitting procedure found a nominal current sheet half-thickness of $0.7 R_S$, the same

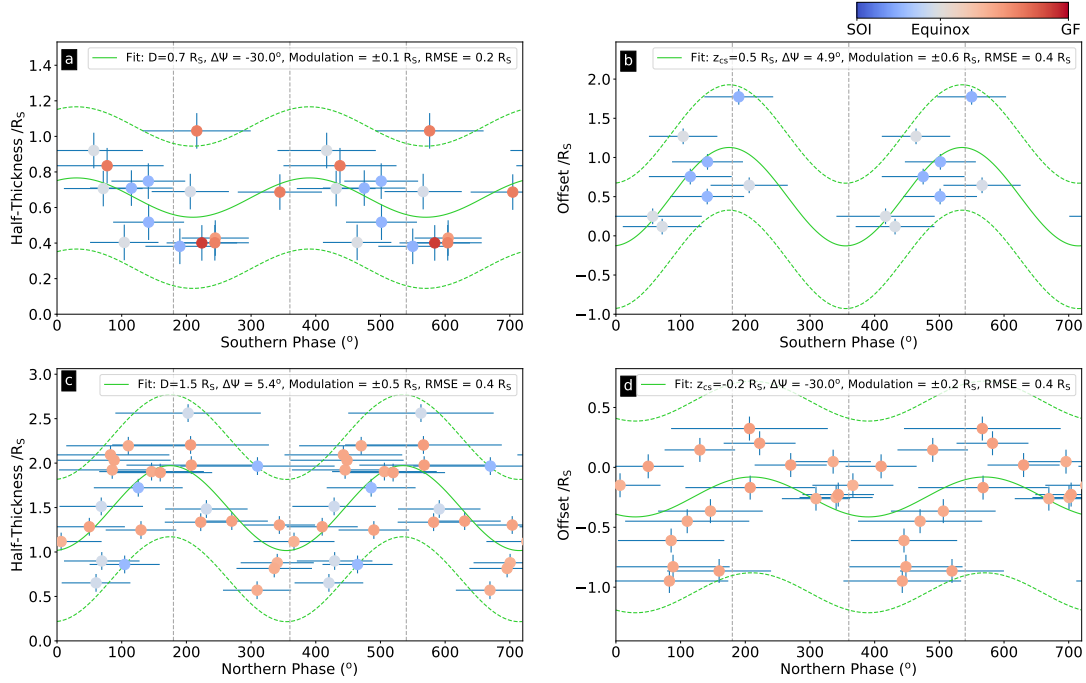


Figure 5.14: Panels a) and c) shows the half-thickness, given by D , for crossings on the nightside in the magnetodisc proper and quasi-dipolar regions as a function of the local southern northern PPO phase, respectively. The fitted sine curve reveals the magnitude of the modulation and the nominal thickness. Panels b) and d) show the calculated offset, given by z_{CS} , and a fitted sinusoid for a subset of the data in a) and c), restricted to events that occurred either pre- or post-equinox. The phase delay, given by $\Delta\Psi$, modulation amplitude, and RMS error of the fit are shown in the legend of each plot. The 95% confidence interval is also shown (as dashed lines) for each fitted sinusoid. Figure taken from Staniland et al. [2020].

as the value found in Figure 5.10. The current sheet half-thickness varies between $0.4R_S$ and $1.0R_S$ and appears to follow a sinusoidal variation quite well, with a RMS error of $0.2R_S$, assuming a modulation of $\pm 0.1R_S$. However, not all the data follows this trend, with an example of a thick current sheet at $\Psi_S^* = 180^\circ$ when it is expected to be thinned. However, if all the thickness modulations were be mapped by a simple sinusoidal variation,

this would assume the only source of variability are the PPOs. Whilst Figure 5.14a) appears to show that the PPOs could be one of the main drivers, there seems to be evidence for other sources of thickness variability.

Figure 5.14b) shows a subset of the data from 5.14a) to analyse the behaviour of the current sheet offset. The data from 5.14a) has more events that occurred before 2009, when the current sheet centre is expected to be positive since it is southern summer, and so we analyse these events. A sine curve was fit to this subset of examples and revealed a central offset value of $0.5R_S$. Using the Arridge et al. [2008a] model gives a hinging distance of $28R_S$ which is within the range of values previously observed [Arridge et al., 2011, Carbary et al., 2015]. However, an assumption here is that the current sheet offset is fixed and any variability is due to the PPOs. The hinging distance has been shown to vary orbit-to-orbit due to variable solar wind forcing [Agiwal et al., 2020] and since our events range over 2 years this assumption might not be valid, so it is difficult to separate these two effects.

The data was shown as a function of the southern PPO phase because the RMS error associated with the fits was smaller compared to the northern PPO phase. This could be reflective of the current sheet being more responsive to the southern PPO current system. Determining the relative strength of the PPO current systems reveals which is dominant. The parameter k is the ratio of the amplitude of the northern PPO system over the southern PPO system and has been calculated for the complete Cassini mission where possible [Andrews et al., 2012, Provan et al., 2013, 2016, 2018]. If $k > 1$ the northern system dominates and if $k < 1$ the southern system dominates. The events in Figure 5.14a) occurred during 2007, 2009, 2013 and 2014. During 2007, $k < 1$ so the southern phase dominated whilst $k \approx 1$ during the second half of 2009 and the first half of 2013. For the rest of the data there is currently no known k value. All the data in Figure 5.14b) occurred before equinox when $k < 1$ and the southern system dom-

inated so it makes sense for the data to be better organised by the southern PPO phase.

Figure 5.14c) shows the thickness of the magnetodisc current sheet in the nightside quasi-dipolar region ($< 15R_S$) as a function of the northern PPO phase. The variations in thickness appear to be somewhat organised by an assumed sinusoidal modulation, with an RMS error of $0.4R_S$. The fit determined a nominal half-thickness of $1.5R_S$, in close agreement with the median calculated using all the data in this region, but slightly thinner, most likely due to our removal of crossings that took longer than a PPO cycle. The half-thickness of the current sheet varies between $0.5 - 2.5R_S$, showing larger variability than in the magnetodisc proper region. Figure 5.14d) shows a subset of the data that occurred post-equinox when the current sheet offset is expected to be negative. The nominal offset was found to be $-0.2R_S$, implying that the hinging distance was $19R_S$, again within the range of previously recorded hinging distances but closer to the planet. The events in Figure 5.14c) occurred during 2007, 2009, 2012 and 2013, where $k \lesssim 1$ except for in 2012 when $k > 1$. All the events in Figure 5.14d) occurred post-equinox when $k \geq 1$ and so this would suggest the data should be better organised by the northern PPO phase. However, the difference in RMS error between southern and northern phase organisation of the offset was smaller compared to the cases in Figure 5.14b). This could be because the dominance of the northern PPO system was weaker in 2012 compared to the dominance of the southern PPO system pre-equinox.

On the dayside there was minimal thickness and offset variability, as previously discussed, and this was not well organised as a sinusoidal variation. In Figure 5.15 the evidence for PPO control is less clear with more examples that do not follow the trend where the current sheet was particularly thick or offset. This could be due to variable upstream solar wind conditions resulting in larger displacements and a thicker current sheet.

We were unable to identify clear evidence of the expected thickness and

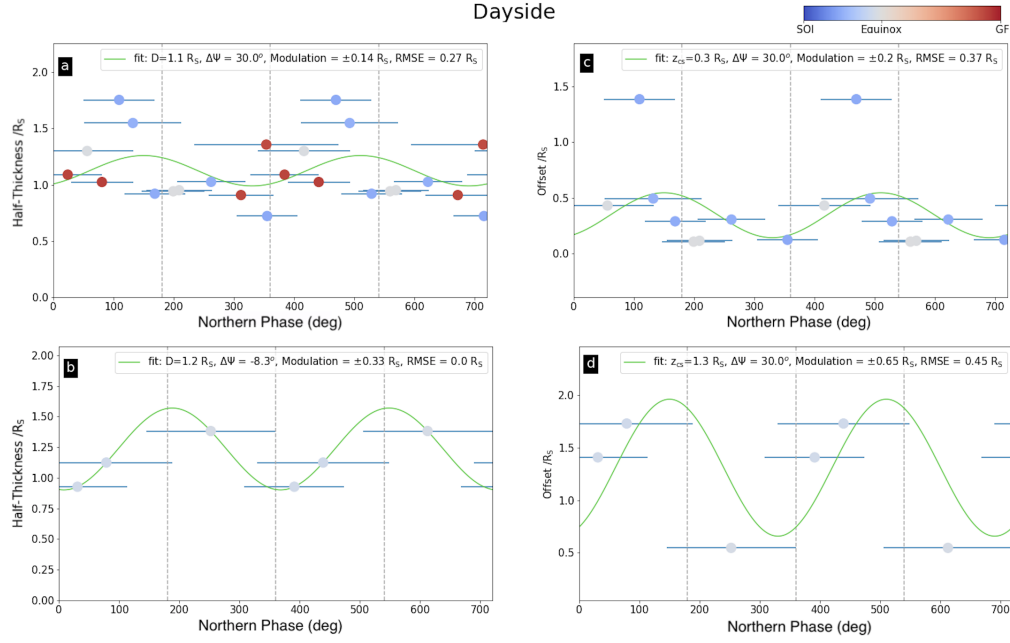


Figure 5.15: Panels a) and c) show the current sheet thickness and offset as a function of northern PPO phase in the dayside quasi-dipolar region. Panel's b) and d) shows the thickness and offset in the same format but for the magnetodisc proper region. We see little correlation with the PPO phases.

offset modulation differences when the PPOs were in-phase or in antiphase conditions that has previously been discussed [Provan et al., 2012, Thomsen et al., 2017, Cowley and Provan, 2017]. For instance, the top two panels of Figure 5.16 shows that on the nightside in the quasi-dipolar region during antiphase conditions we see a sinusoidal variation in the current sheet thickness. However, the bottom two panels in Figure 5.16 shows that during in-phase conditions, whilst the range of measured thickness values is reduced as we would expect, the variability is not well mapped by the simple sinusoidal relation. It should be noted that the set of crossings occur throughout the complete Cassini mission and so k is variable between events. This changes the expected modulation of the thickness and offset

by the PPOs. In addition, the $\pm 90^\circ$ range for the in-phase and anti-phase conditions introduces cases when the PPO systems were in quadrature. This could make identifying the differences between these two conditions less clear.

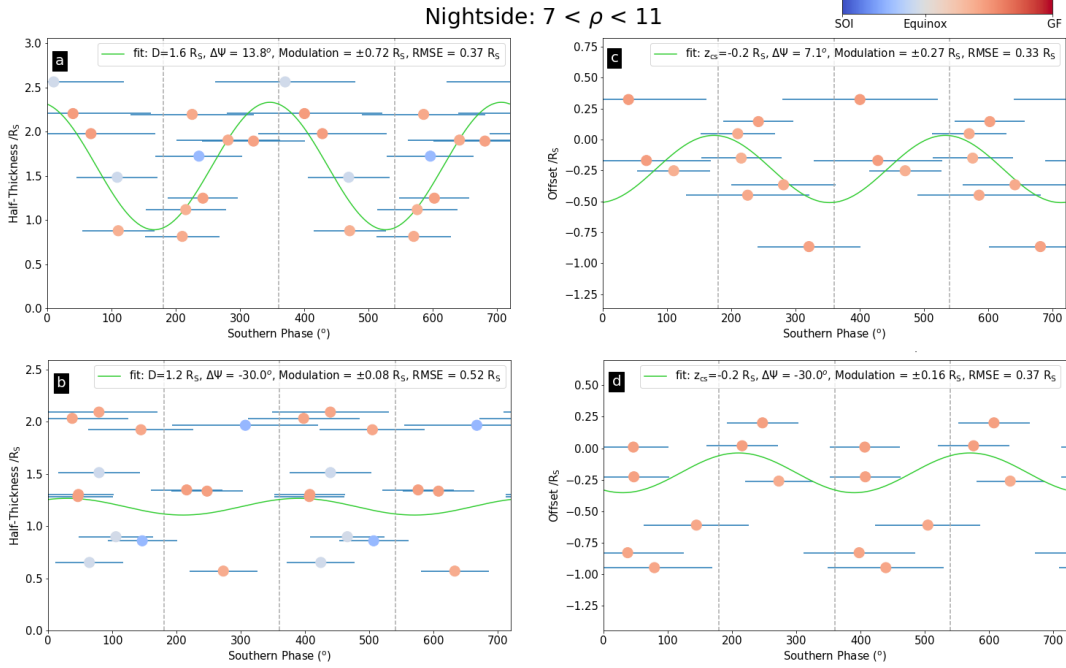


Figure 5.16: Panels a) and c) show the current sheet thickness and offset as a function of southern PPO phase in the nightside quasi-dipolar region during anti-phase conditions. Panel's b) and d) shows the thickness and offset for in phase conditions in the same format.

5.4 Conclusions

We have determined the nominal thickness of the magnetodisc current sheet and analysed potential sources of variability. Using a simple variance analysis the thickness was directly determined when Cassini made

fast and steep crossings of the current sheet. The average half-thickness of the current sheet is $1.3R_S$ but evidence for spatial and temporal variability were found.

On the dayside the current sheet has an average half-thickness of $1.1R_S$ and remains at approximately constant thickness with respect to radial distance from the planet. This most likely reflects the compression of the dayside magnetosphere by the solar wind. On the nightside the average current sheet half-thickness is $1.3R_S$ which is marginally thicker than the dayside but a larger range of values were observed on the nightside, showing this to be a more variable sector of the magnetosphere. The current sheet is thicker close to the planet than the dayside with a half-thickness $1.7R_S$ compared to $1.1R_S$. These results are consistent with and support the presence of a noon-midnight electric field at Saturn that produces a hotter plasma population on the nightside compared to the dayside. The current sheet also gets thinner with radial distance on the nightside as the magnetic field stretches into the magnetotail.

The variability in thickness was shown to be somewhat characterised by the PPOs. We found that the day-night asymmetry in thickness in the quasi-dipolar region could not be explained by a PPO beat phase bias being sampled by Cassini. The current sheet was thinner during in phase conditions and thicker during antiphase conditions in both local time sectors. Some of the thickness variations between events in each local time and radial sector could be described by a simple sinusoid that is a function of the northern and southern PPO phases. These were better correlated on the nightside compared to the dayside where little PPO control was observed. These results are suggestive of other sources of variability that cannot be captured by this simple sinusoidal relationship. For instance, hot plasma injections following nightside reconnection can sporadically thicken the current sheet [Provan et al., 2021].

These results reveal how the large-scale structure of the current sheet

responds to processes that drive dynamics at Saturn. The thickness values calculated are essential for accurately modelling the current sheet and show the requirement for considering both the spatial and temporal variability of the main current system in the Saturnian magnetosphere.

Chapter 6

The Cushion Region at Saturn

The large-scale structure of the Saturnian magnetosphere is shaped by the magnetodisc current sheet. In the previous chapters the current sheet geometry and its variability was discussed. This final chapter will explore the limits of the magnetodisc structure, when it might break down, and what triggers disc instabilities.

At the gas giants, the presence of an internal plasma source coupled with their rapid rotation radially stretches the field from a dipole into a magnetodisc. This structure has been observed at all local times under expanded conditions at Saturn [Arridge et al., 2008b]. At Jupiter, a region adjacent to the magnetopause where the magnetodisc structure breaks down and the field is quasi-dipolar, referred to as the “cushion region”, has been identified [Went et al., 2011b] and is argued to be populated by mass-depleted flux tubes following tail reconnection [Kivelson and Southwood, 2005]. A sketch of the cushion region at Jupiter is shown in Figure 6.1. However, this region has yet to be identified at Saturn [Went et al., 2011b] despite the similarities between these two systems. The magnetosphere of Saturn is often described as being between Earth’s and Jupiter’s in terms of structure and dynamics. This study provides an opportunity to elucidate this comparison.

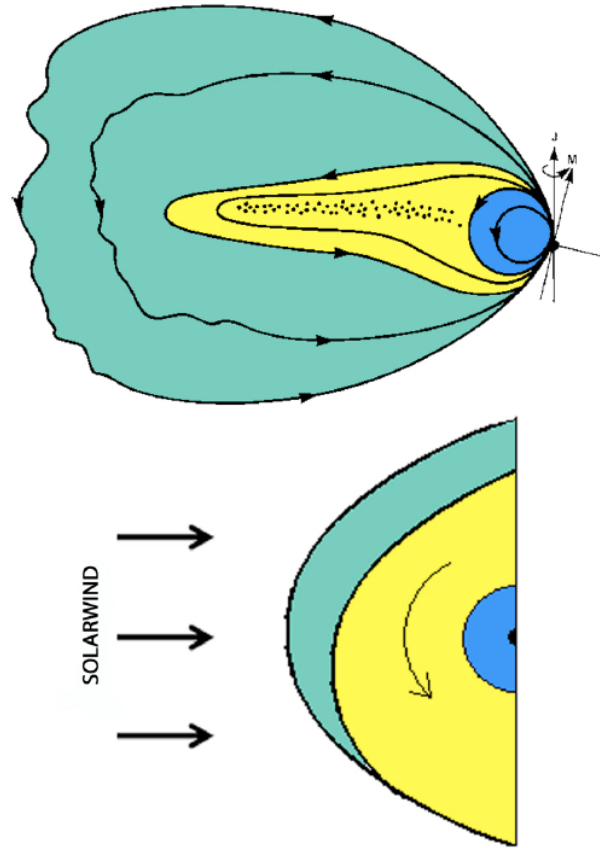


Figure 6.1: Sketch from Went et al. [2011b] showing (not to scale) the cushion region at Jupiter. The top sketch shows a meridional slice of the Jovian dayside magnetosphere, where the blue region indicates the dipolar inner region, the yellow shows the middle disc region populated by plasma sourced from the moon Io and the green shows the quasi-dipolar cushion region in the outer magnetosphere. The bottom sketch is an equatorial projection of the the same configuration, showing the cushion resides between the disc outer edge and magnetopause in the dawn to noon local time sectors.

At Saturn plasma sourced from Enceladus must be lost from the magnetosphere. These W^+ water group ions are eventually driven radially outwards in the low plasma beta ($\beta < 1$) inner magnetosphere via an inter-

change instability with the more tenuous hot plasma population in the outer magnetosphere [e.g. Gold, 1959, Azari et al., 2018]. At larger radial distances, plasma pressure dominates ($\beta > 1$) and the magnetic field balloons until closed field lines reconnect and mass is lost in the magnetotail [Vasyliunas, 1983]. These mass-depleted flux tubes following nightside reconnection via this cycle, or the solar-wind driven Dungey cycle [Dungey, 1961] are eventually refilled allowing the mass transport cycle to restart.

At Jupiter a channel of mass-depleted flux tubes has been found to reside between the current sheet outer edge and the magnetopause in the dawn to noon local time sectors. This is shown in Figure 6.1. In the cushion region (shown in green) the field geometry is quasi-dipolar due to the lower plasma content and a break down of the disc force balance. This region is regarded as a signature of the mass loading and unloading cycles described above [Kivelson and Southwood, 2005, Went et al., 2011b] with the volcanic moon Io providing the internal source of plasma in the Jovian system. At Jupiter, the cushion region has been found to preferentially arise at dawn, with a nominal inner boundary of $54R_J$ ($R_J = 71,492$ km is the radius of Jupiter) compared to a nominal standoff distance of $75R_J$, indicating a cushion region thickness $\sim 20R_J$ but with significant variability in the location of these boundaries. Went et al. [2011b] suggest that if we scale their Jupiter observations to Saturn we would expect a $6R_S$ thick cushion region.

Signatures of a dipolar field in the outer magnetosphere do not necessarily require mass-depleted flux tubes following nightside reconnection. Short, sharp decreases in B_θ in B_θ dominated environments, known as ‘magnetic nulls’, have been observed in the outer magnetosphere of Jupiter and are suggested to be signatures of dense plasma clumps breaking off the disc [Southwood et al., 1995]. Negative B_θ signatures are interpreted as the spacecraft measuring the northward directed inner edge of the closed magnetic loop following disc reconnection. Once plasma escapes the edge

of the disc the plasma blobs are squeezed by the local dipolar magnetic field and extend along the field. Disc reconnection could be induced for instance by low solar wind pressure when the magnetosphere expands allowing the disc to balloon [Southwood and Kivelson, 2001]. In addition, Goertz [1983] found evidence of dense flux tubes outside the current sheet that are due to centrifugal instabilities of a rotating plasma. They argue that this instability can also disperse plasma sourced from Titan. Hence, the cushion region acts as a buffer between the current sheet outer edge and the magnetopause. However, since the arrival of Juno Gershman et al. [2018] found there lacked a systematic cushion region at Jupiter, possibly highlighting that this dynamical picture of mass loss and return flow is incomplete.

Supercorotating return flow of energised water group ions following Vasyliunas-type reconnection has been identified at dawn at Saturn [Masters et al., 2011b]. Jasinski et al. [2019] identified a region of electron depleted flux tubes in the morning sector using the data from the CAPS ELS instrument [Young et al., 2004]. However, a quasi-dipolar structure has not been observed in the magnetic field data [Went et al., 2011b]. Plasma is being lost from the system and empty flux tubes must inevitably refill but thus far there has been no evidence for a cushion region at dawn that acts as a return flow channel.

The magnetodisc is often modelled using a two-dimensional force balance model [e.g. Caudal, 1986, Achilleos et al., 2010, Chou and Cheng, 2010]. These models incorporate an equatorial current sheet that produces a disc-like region in the middle magnetosphere and dipolar region in the outer magnetosphere. In addition, Delamere et al. [2015] found evidence of patchy ‘drizzle-like’ reconnection ($B_\theta < 0$) predominantly in the noon to dusk sectors and evidence of intermittent dipolar fields in the outer magnetosphere where the field strength is greater than the planetary dipole. They suggest that this outer dipolar region that is also seen in the equilibrium

models is an accumulation of expelled flux from the current sheet. However, analysis of the magnetic field data has yet to observe this as a large-scale region in the outer magnetosphere of Saturn [Went et al., 2011b]. Using data as Cassini traverses the dayside magnetosphere, it has been found that the radial disc field can extend up to the magnetopause [Arridge et al., 2008b]. Hence, to identify the presence of a cushion region that is sustained over large-scales an analysis of how the global magnetic field structure varies with distance from the planet is required. This study will use the complete Cassini orbital magnetometer dataset at Saturn [Dougherty et al., 2004] to look for the first evidence of a cushion region at Saturn.

This work contributed to the publication of Staniland et al. [2021].

6.1 Data Selection

To search for a cushion region at Saturn, all Cassini orbits that traversed the dayside inner magnetosphere out to the magnetopause, whilst remaining near the equator ($\pm 30^\circ$) are analysed to track changes in the magnetic field configuration. Crossings of the dayside magnetopause are identified using the Jackman et al. [2019] catalogue. The nose standoff distance R_{SS} for each magnetopause crossing, using the crossing closest to the planet if there are multiple during a single traversal, is mapped with the Pilkington et al. [2015b] dawn-dusk asymmetric magnetopause model. We create a 3000-element array of potential dynamic pressures D_p ranging from 0.0001 nPa to 10 nPa, matching the range of upstream measurements [Jackman and Arridge, 2011a]. We then calculate the magnetopause crossing radial position r using D_p and the given latitude and azimuth from the Jackman et al. [2019] list, iterating this process through the D_p array until r matches the observed value to one decimal place. This value of D_p is used to calculate R_{SS} using Equations 2.10. The Pilkington et al. [2015b] local time correction only introduces a maximum $\pm 0.5 R_S$ difference in R_{SS} compared to

an axisymmetric model, but it is included for completeness. The 92 suitable Revs that fulfil the above criteria are shown in Figure 6.2 along with the mapped standoff distances that range from $14.5 - 35.0 R_S$.

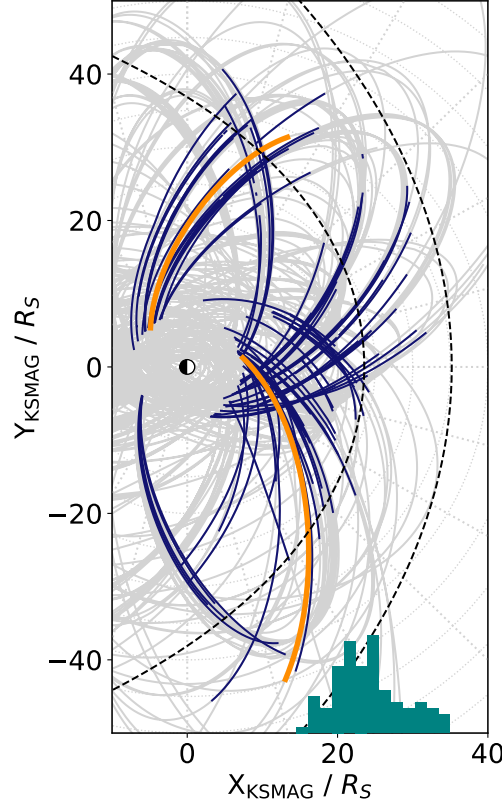


Figure 6.2: The complete Cassini orbital mission trajectory is shown in light grey, projected onto the equatorial plane where the Sun is to the right. The trajectory of Cassini during the 92 Revs used in this study is shown in dark blue. The orange trajectories show the case studies in Figure 6.3. Magnetopause [Pilkington et al., 2015b] and bow shock [Went et al., 2011a] models, assuming solar wind dynamic pressure of 0.01 nPa, are shown with black dashed curves. The histogram shows R_{SS} for each crossing. Figure from Staniland et al. [2021].

6.2 Finding the Cushion Region

For each Rev we track the magnetic field configuration as Cassini samples the dayside magnetosphere from the inner region out to the magnetopause. We begin by subtracting the Dougherty et al. [2018] internal magnetic field model from the orbital magnetometer data to identify contributions from external fields such as the current sheet. An 11-hour (approximate rotation period) sliding average of the magnetometer data in KSMAG spherical coordinates is taken to focus on the global structure and filter out other variability, including the ubiquitous planetary period oscillations (PPOs) (see Carbary and Mitchell [2013] review and references therein). We use the Jackman et al. [2019] magnetopause catalogue to identify magnetopause crossings and determine when Cassini is within the magnetosphere of Saturn. This catalogue also includes information on characterizing boundary layers that we used to ensure our measurements were not in this region. Nonetheless, boundary layer crossings occur on much smaller time-scales ($\sim$ minutes) [Masters et al., 2011a] than the cushion region traversals we have identified ($\sim$ hours to days) and so should not affect our results.

To identify whether a cushion exists, there must be a stable disc structure in the middle magnetosphere, otherwise the field could be quasi-dipolar everywhere. There are two conditions for the field to be disc-like [Went et al., 2011b]. Firstly, the field must be predominantly radial such that $B_r^2/B^2 > B_\theta^2/B^2$. These ratios are shown in panels b) and e) of Figure 6.3. However, this criterion is insufficient when Cassini is away from the equator, where a dipole field is not purely north-south. This is particularly important to consider if the current sheet is warped [Arridge et al., 2008b]. To account for this, the second criterion is for the angle between the measured magnetic field and a dipole, where we have used the Dougherty et al. [2018] model, to be $90 \pm 30^\circ$. This angle is shown in panels c) and f) of Figure 6.3. When both these criteria are satisfied, the field is disk-like.

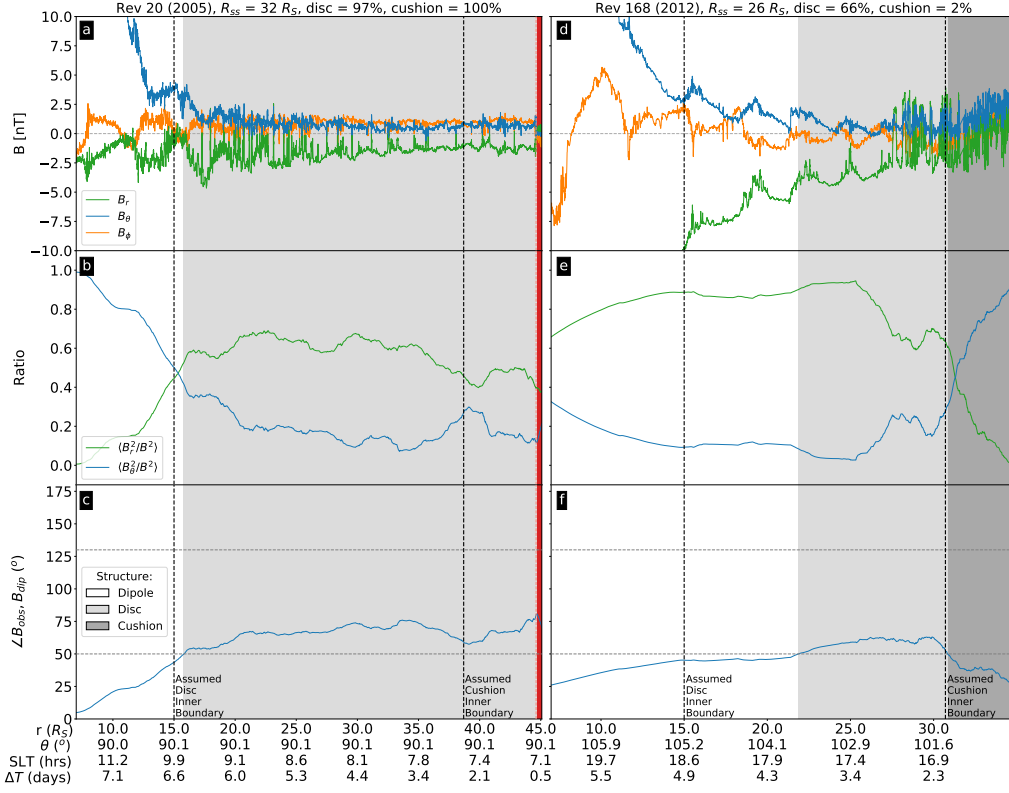


Figure 6.3: Two examples of Cassini traversing the equatorial dayside magnetosphere are shown as a function of radial distance. The top panels show the 1-minute resolution field data in spherical coordinates. The second panels show the ratio of the 11-hour smoothed radial and meridional components to the total field. The bottom panels show the angle between the measured field and the Dougherty et al. [2018] internal magnetic field model. These identify the structure of the field. The panels are shaded to show if the field is dipole-like (white), disc-like (light grey), cushion-like (dark grey), or in the magnetosheath (red). The assumed disc and cushion region boundaries are shown as vertical dashed lines. The left panels show an example at dawn where the magnetodisc is present up until the magnetopause, whilst the right panels show an example at dusk where a cushion is identified. At the bottom of the figure the radial distance (r), co-latitude (θ), Saturn local time (SLT), and time from magnetopause crossing (ΔT) are shown. Figure from Staniland et al. [2021].

The location 80% of the distance from the $15R_S$ disc inner edge [Arridge et al., 2008b] to the magnetopause is set as the cushion region inner edge. For instance, if the magnetopause radial position is $r = 25R_S$ the cushion inner edge is $r = 23R_S$. Whilst this is closer to the magnetopause than the average inner boundary of the Jovian cushion [Went et al., 2011b] it is chosen due to the lack of an observed cushion thus far and the smaller magnetosphere of Saturn. It is also far enough from the magnetopause to assume we are not measuring the shielding of the field by the boundary currents, although previous evidence of the disc persisting up to the magnetopause [Arridge et al., 2008b] shows that this effect should be negligible. We then calculate what percentage of the data fulfil the two criteria in the disc region (from $15R_S$ to the cushion inner edge). If it is more than 50% we suggest that there exists a stable magnetodisc structure. In the remaining layer up to the magnetopause, if this percentage remains approximately constant, the field is still disc-like. If the percentage significantly reduces and the field becomes more dipolar, there is a cushion. If less than 50% of the disc region has fulfilled the criteria, there is no stable magnetodisc and so we cannot check whether there is a cushion present. This ensures we see two distinct regions with persistent and sustained structures.

The change in percentage across these two regions for all 92 Revs was calculated. The mean was a reduction by $\mu = 6\%$ with a standard deviation of $\sigma = 24\%$. We define those Revs whose reduction in percentage is greater than $\mu + 2\sigma = 54\%$ as having a cushion. This is large enough to consider these as examples of a cushion and not an artefact of our method compared to if, for instance, $\mu + 2\sigma$ was only 10% reduction.

6.3 Results

For Rev 20 in Figure 6.3, the disc criteria are satisfied for 97% of the disc region and for 100% of the cushion region, showing an example of a stable

magnetodisc structure that persists up to the magnetopause. The mapped standoff distance R_{SS} for Rev 20 was $32R_S$ showing that the system was expanded ($R_{SS} > 23R_S$). For Rev 168, the criteria are satisfied for 66% of the disc region. However, the percentage drops to just 2% in the cushion region and the field becomes significantly more dipolar. For Rev 168, $R_{SS} = 26R_S$ showing the system was expanded. We suggest that this is the first evidence of a cushion region observed at Saturn.

A potential explanation for the Rev 168 cushion region could be that the dipolar outer boundary reflects the change in local time as Cassini moves away from noon (in time) and the magnetopause confinement of the field reduces. However, Cassini only passed through 0.2 hours of local time in the cushion region, and 1.2 hours between where the disc was first observed and the cushion region inner edge, producing only a small change in the magnetopause radial position. In addition, Revs with a similar noonward trajectory where a disc was observed at dawn did not observe a dipolar outer region. Another explanation could be that the magnetosphere underwent a sudden solar wind compression. Whilst for the Rev 168 there is a small increase in magnetic field strength (~ 1 nT), the data are particularly noisy in this region and the cushion was observed radially inwards of this small increase. In addition, we compared the field profile for all five potential examples of a cushion region and saw no significant increase in field strength to suggest that these are results of solar wind compression.

This analysis was carried out for all 92 Revs. Only 15 Revs had a sustained magnetodisc and are shown in Figure 6.4a) in grey. The disc formed not only when the magnetosphere was expanded but when R_{SS} was as low as $17R_S$. Of these 15 Revs, five are examples of cushion regions and are highlighted in Figure 6.4a) in blue. For all cushion region examples $R_{SS} > 23R_S$ with a mean value of R_{SS} is $25.9 R_S$. However, a cushion does not arise whenever the magnetosphere is expanded. In particular, it does not arise preferentially at dawn as was expected. We show all the cushion

region examples identified in this study in Figures 6.5, 6.6, 6.7 and 6.8.

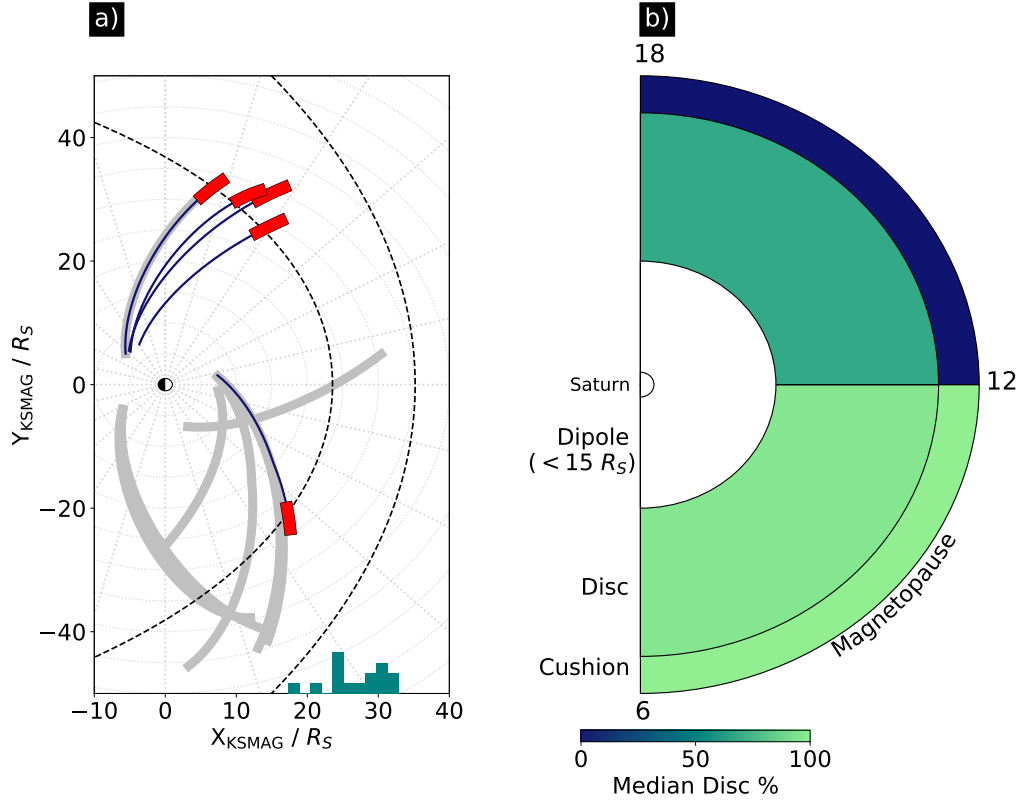


Figure 6.4: Panel a) shows the 15 Cassini Revs where a stable disc was identified in the same format as Figure 6.3. The five cushion examples are shown in blue, with the cushion highlighted in red. Panel b) shows a representation of the average dayside configuration calculated using the 15 examples in panel a). The three radial sectors of dipole, disc, and cushion are labelled and the dayside is divided into dawn and dusk local time sectors with the 15 Cassini Revs categorised by the local time position of the magnetopause crossing. The colorbar shows the median disc percentage. There is a distinct disc structure at dawn that persists up to the magnetopause (light green). At dusk, on average there is a less stable disc in the disc region (dark green) and the field becomes more dipolar in the cushion region (blue). Figure from Staniland et al. [2021].

In panel b) of Figure 6.4 the average magnetic field structure calculated

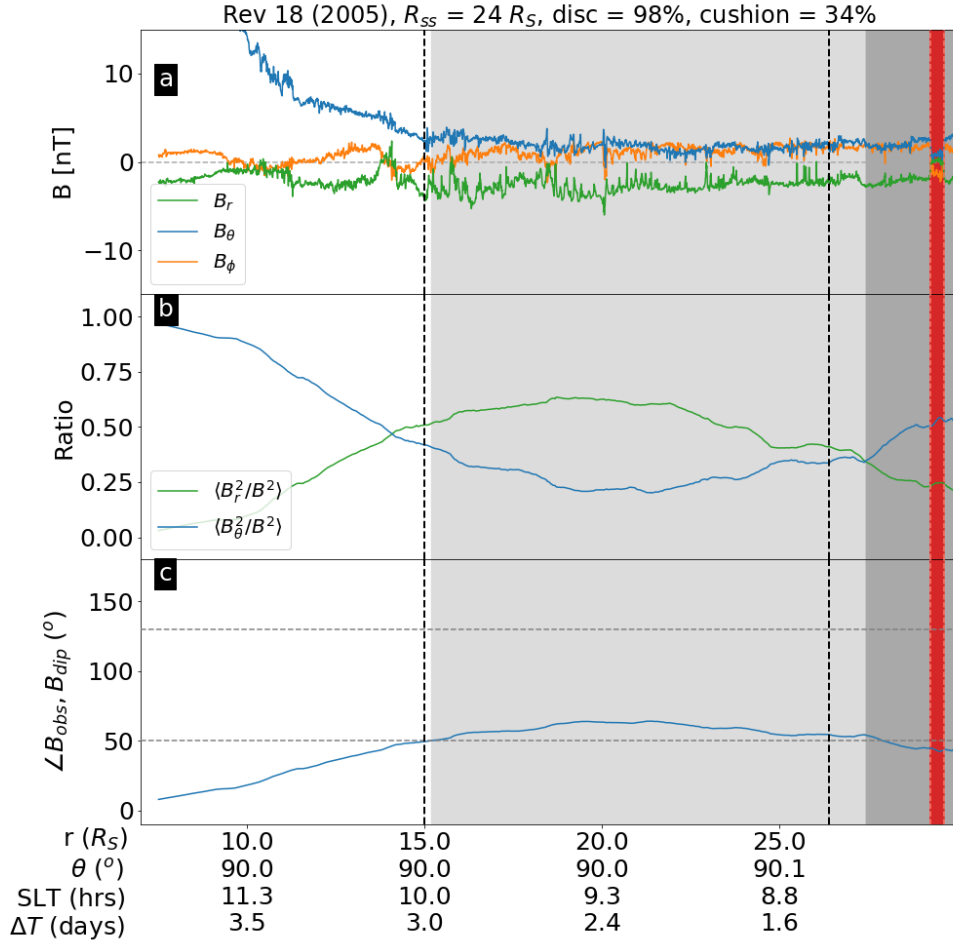


Figure 6.5: Magnetic field data from Rev 18 showing another example of a cushion region at Saturn. The format is the same as Figure 6.3 and this format will be used for the rest of the cushion examples shown. Similar to Rev 168, a sustained disc region is observed in the middle to outer magnetosphere but the field becomes quasi-dipolar close to the magnetopause. However, Rev 18 differs to the rest of the examples since Cassini was traversing the pre-noon sector when the cushion was identified.

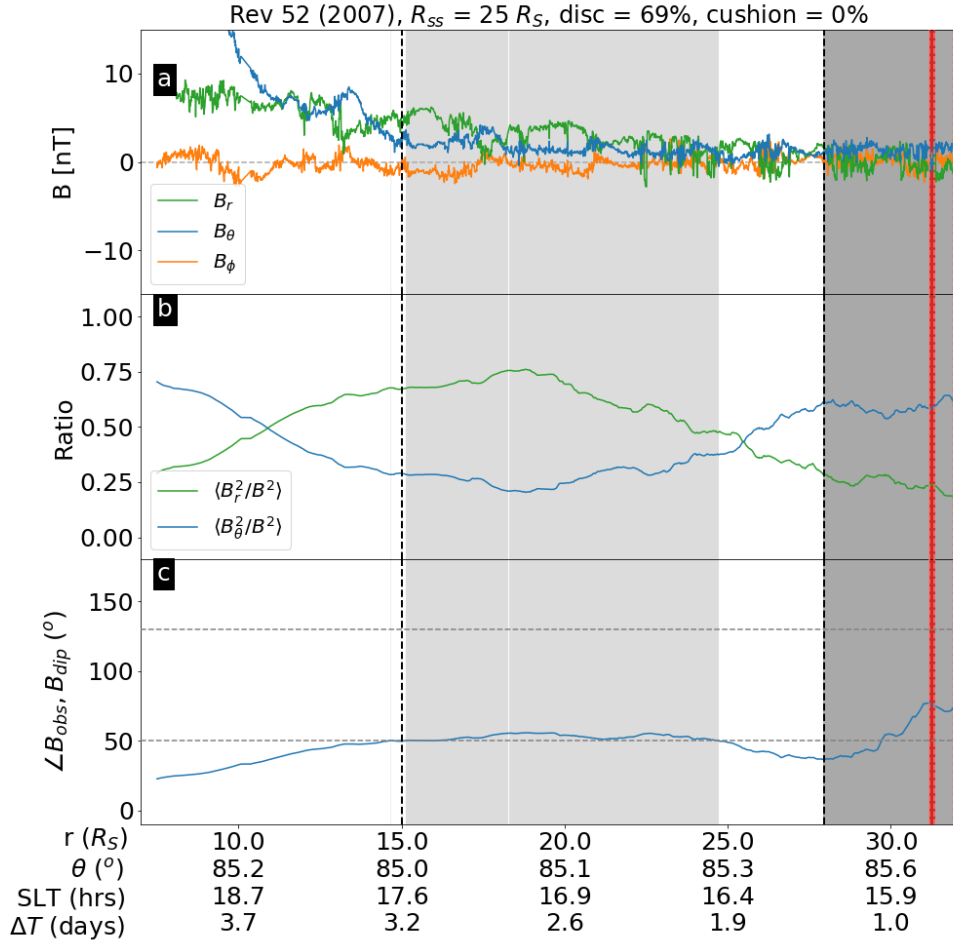


Figure 6.6: Cushion region identified during Rev 52 in the dusk sector, shown in the same format as the previous figure. Here the field is disc-like up until $25R_S$ when the two criteria are no longer satisfied and the field is quasi-dipolar. Note that the angle between the observed field and the dipole model increases towards 90° near the magnetopause boundary, but this is due to the sliding window average being affected by measurements in the magnetosheath. This does not affect our determination of the field structure in this region.

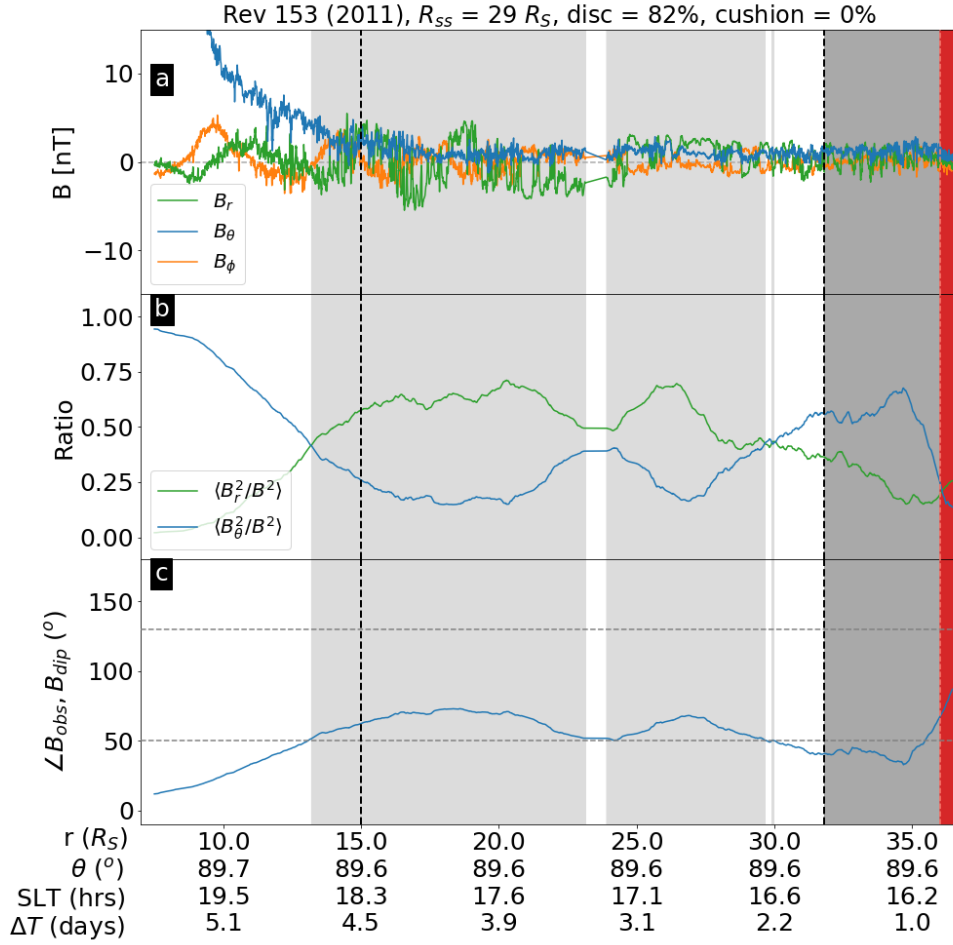


Figure 6.7: Cushion region identified during Rev 153 in the dusk sector. For this example, the field structure appears more variable in the middle magnetosphere region. This effect is most likely PPO driven modulations of the magnetic field and current sheet.

using this subset of 15 Revs with a sustained magnetodisc is shown, revealing a local time asymmetry in our dataset. When there is a magnetodisc at dawn, the structure is stable in the disc region (median of 95% for

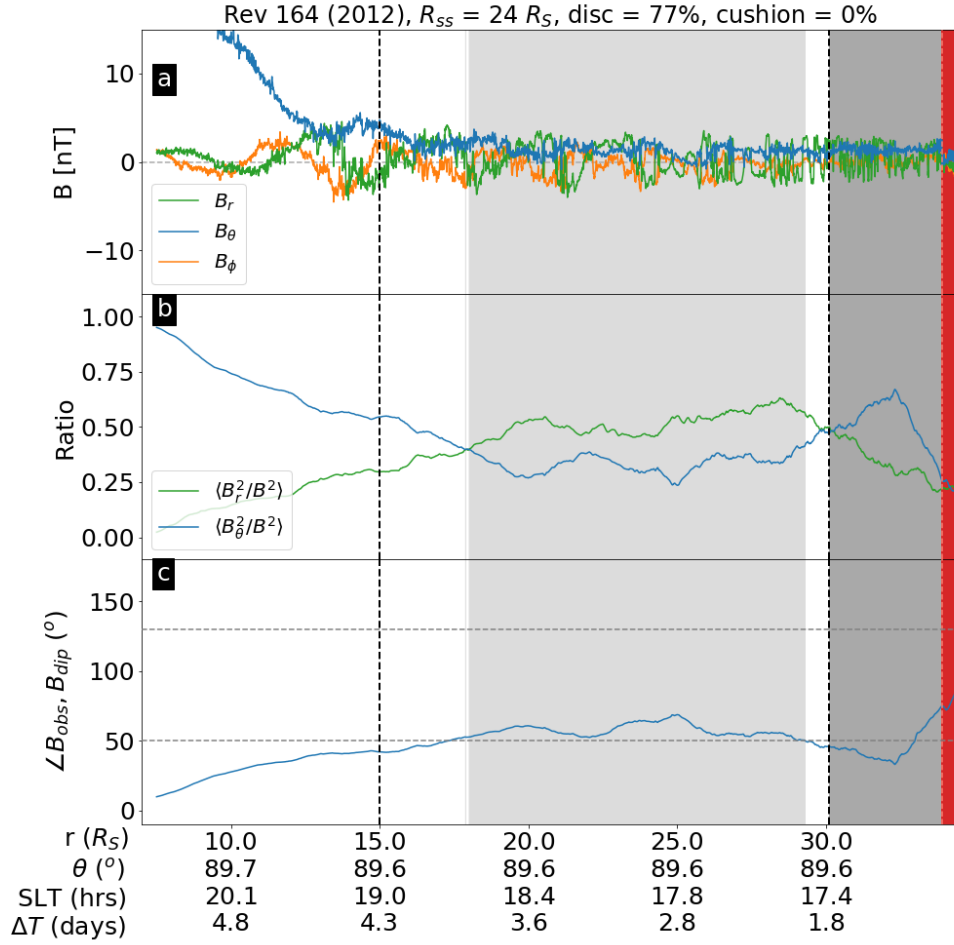


Figure 6.8: Cushion region identified during Rev 164 in the dusk sector. This example is most similar to the cushion region observed during Rev 168.

nine Revs) and this continues into the presumed cushion region (median of 100%). At dusk, when there is a magnetodisc it is on average less stable in the disc region (median of 68% for six Revs) and this significantly drops in the cushion region (median of 1%). There are two examples of a stable disc

that persists up to the magnetopause at dusk, compared to eight at dawn. If the mean percentage is used for Figure 3b), the one cushion example at dawn makes the cushion region a darker green. However, due to the small number of examples in the dataset the median is used instead.

6.3.1 Significance Test

The statistical significance of the dawn-dusk asymmetry observed can be analysed. The Fisher's exact test is used to firstly test the null hypothesis that disc formation is local time symmetric. This hypothesis test is used when the sample size is small such that all possible combinations of the data can be calculated, giving us an exact probability, or p -value. A 2×2 contingency table is of the number of Revs/events where a dipole or a disc was observed is created and shown in Table 6.1. Only Revs where $R_{SS} \geq 23R_S$ are included since disc formation also depends on system size and is more likely to be observed when the standoff distance is at least this large [Arridge et al., 2008b]. The null hypothesis suggests that the observations should be uniformly distributed given our marginal totals. The Fisher's exact test is used to try and reject this null hypothesis and establish how unlikely these observations are by calculating the probability of all possible scenarios and finding the sum of the probabilities of either our results or results more extreme occurring. If the probability is less than 0.05 the null hypothesis can be rejected showing that disc formation is local time asymmetric. A one-sided test is chosen to identify whether disc formation occurs preferentially in one local time sector, not just that it is asymmetric.

Using data from Table 6.1 the one-sided Fisher's exact test gives $p = 0.008$ showing that disc formation is local time asymmetric and preferentially arises at dawn. This corroborates with the results shown in Figure 6.4 and shows that these findings are statistically significant.

Next, a one-sided Fisher's exact test for the cushion events is performed.

	Dawn	Dusk
Dipole	8	28
Disc	6	2

Table 6.1: Number of disc events per local time sector.

	Dawn	Dusk
Dipole	8	28
Cushion	1	4

Table 6.2: Number of cushion events per local time sector.

Using data from Table 6.2 it is found that $p = 0.731$ showing that the null hypothesis cannot be rejected and the observed dawn/dusk asymmetry is not statistically significant.

For both tests, the standoff distance threshold was varied to account for the system size dependence of disc formation. Figure 6.9 shows that varying the minimum standoff distance does not make the p -value for the cushion formation test fall below 0.05.

This test aimed to identify whether there is a higher probability of observing the cushion at dusk than dawn. Whilst the observed cushion asymmetry is not statistically significant, even a few cases of a dusk cushion suggests that it cannot be described as a return flow channel populated by empty flux tubes following tail reconnection. That couple with the rarity of observing a cushion at Saturn suggests that another formation mechanism is required to explain these observations.

6.3.2 The Effect of Sliding Averages

For this study, the focus is on whether a significant portion of the outer boundary is persistently quasi-dipolar, reflective of the cushion region that has been observed at Jupiter, rather than being intermittently quasi-dipolar. An 11-hour average of the magnetic field data was taken to focus on the large-scale properties of the magnetic field structure. Some examples of what appear to be an intermittent cushion were therefore removed from our analysis. The field structure signatures at dusk are far noisier, which is reflected in the low disc region percentage at dusk in Figure 6.4. In Fig-

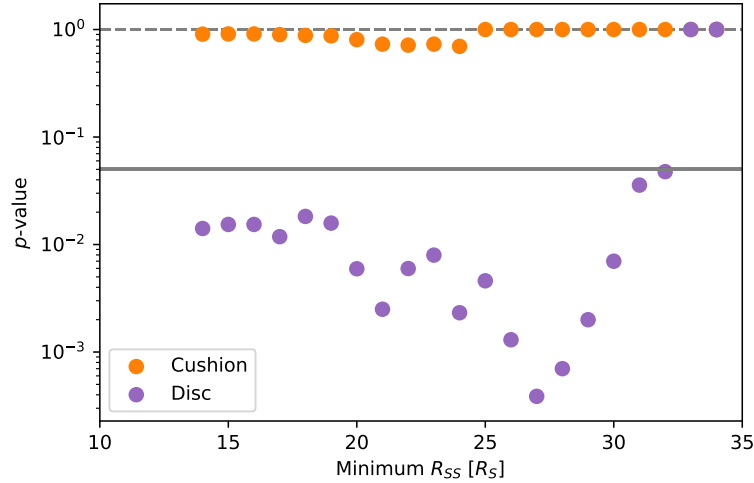


Figure 6.9: The p -value from the Fisher's exact test was used to determine whether disc and cushion formation at Saturn is local time asymmetric. For this test the system size dependence on disc, and therefore cushion, formation must be removed. This plot shows how p varies with choice of minimum standoff distance. The horizontal black line shows $p = 0.05$ and the dashed black line shows $p = 1$. This shows that $p \leq 0.05$ for almost all choices of R_{SS} when testing the statistical significance of disc asymmetric formation, implying the disc structure is more likely to be observed at dawn than dusk. However, $p \not\leq 0.05$ for any choice of R_{SS} showing that dusk cushion formation is not statistically significant based on our observations.

Figure 6.10 Rev 164 is shown again but having not taken the 11-hour sliding average of the magnetic field. The electron temperature and density [Lewis et al., 2008] and PPO phases are also shown. The disc percentage has dropped and the cushion percentage has increased without the sliding average, highlighting the variable structure in the dusk sector.

Note that without the sliding averages, whilst some of the percentages from our events changed, most were still tagged as a cushion example in our survey. Towards the far right of the Figure 6.10 an enhancement in

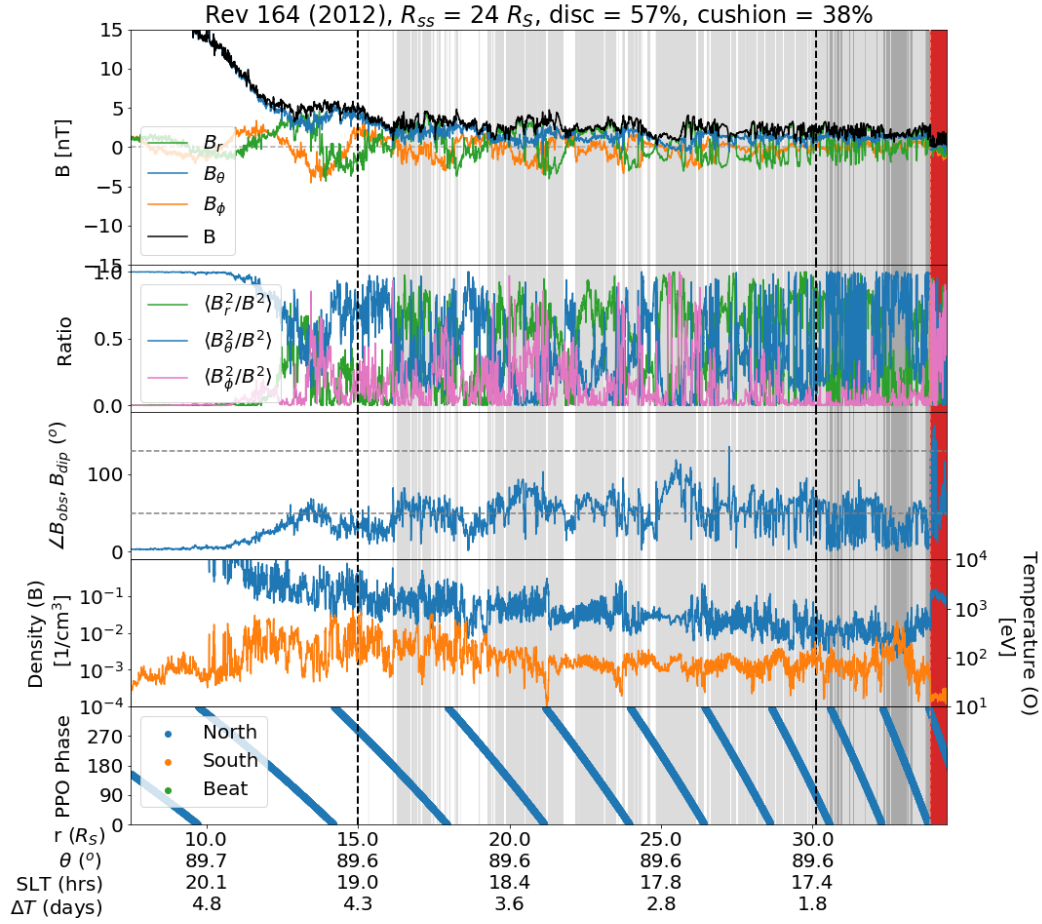


Figure 6.10: Magnetic field, plasma (second bottom panel) and PPO data (bottom panel) for Rev 164 without taking the 11-hour sliding average of the magnetic field data, shown in a similar format to the previous figures. We see that the disc signature is more noisy than when taking the average, as we would expect. This example shows the local plasma properties of the cushion where the electron temperature increases and density decreases, indicating a plasma depleted but energised environment in the cushion region.

the electron temperature and drop in density coincides with the cushion observed in the outer magnetosphere (dark grey background). This indicates a depleted but locally energised plasma population in the cushion region. For the other four cushion examples either a less clear signature in the plasma moments was observed or there was no available data due to CAPS being turned off.

6.4 Discussion

The magnetodisc structure maintains an equilibrium between the outward directed centrifugal force, the magnetic and plasma pressures, and the magnetic field tension in the curved geometry that provides the inward centripetal force required to enforce subcorotation. This is described in Equation 2.5. The field radius of curvature R_C supports this equilibrium. Magnetodisc break down can occur when this radial stress balance is disrupted and the magnetic field can no longer contain the plasma. Ballooning of the disc occurs when the outward-directed plasma parallel pressure dominates the perpendicular pressure plus the inward-directed magnetic tension associated with the curved field geometry. This instability can lead to reconnection and plasma breaking off the disc [Southwood and Kivelson, 2001, Kivelson and Southwood, 2005]. To identify where force balance in the disc might break down, we can examine the magnetodisc MHD force balance approximation given by Equation 2.5 where the left-hand side of the equation contains the magnetic curvature force. Comparison of the gyroradii of heavy ions in each local time sector to the radius of curvature R_C associated with the disc geometry will reveal when this approximation breaks down.

The typical ion gyroradius of a charged particle can be expressed as

$$r_i = \frac{\sqrt{2mk_bT}}{|q|B}, \quad (6.1)$$

where m is the particle mass, q is the charge, B is the local magnetic field strength, T is the temperature where we assume that $T = (2T_{\perp} + T_{\parallel})/3$ and k_b is the Boltzmann constant. Went et al. [2011b] calculated the critical density of the disc under which stress balance would break down. However, due to a lack of data close to the magnetopause at Saturn they could not resolve whether the measured current sheet density in the outer magnetosphere approached the critical density. Now the Cassini mission is complete, we can build on their work using the latest results to understand these new cushion observations.

The Jackman et al. [2019] catalogue of magnetopause crossings from the entire mission is used to determine when Cassini is within the magnetosphere. Having removed all data from outside the magnetosphere a mean equatorial ($\pm 20^\circ$) magnetic field strength radial profile for the dawn (6-12 LT) and dusk (12-18 LT) sectors can be calculated. We find the mean magnetic field strength B in $2.25R_S$ radial bins ranging from $10 - 50R_S$ that are within $\pm 20^\circ$ of the equator. The $\pm 1\sigma$ magnetic field strength profiles are also determined to capture the variability. These are shown in Figure 6.11 where we see the average magnetic field strengths in each local time sector is of a similar order of magnitude, particularly at smaller radial distances. Close to the outer magnetosphere, it appears that the field strength at dusk is slightly lower.

An unexpected observation at Saturn is the non-adiabatic increasing temperature of thermal ions with distance from the planet [Wilson et al., 2017]. A possible mechanism for this heating could be the transport of energy from fluctuating magnetic fields to the magnetospheric plasma via wave-particle interactions. Plasma perturbations, such as outwards radial transport, modify local stress balance and produce magnetic field fluctuations and Alfvén waves. Oppositely directed Alfvén waves interact non-linearly and trigger an energy cascade from large to small scales [Saur, 2004]. At Jupiter, Saur et al. [2018] showed the first plasma kinetic length-

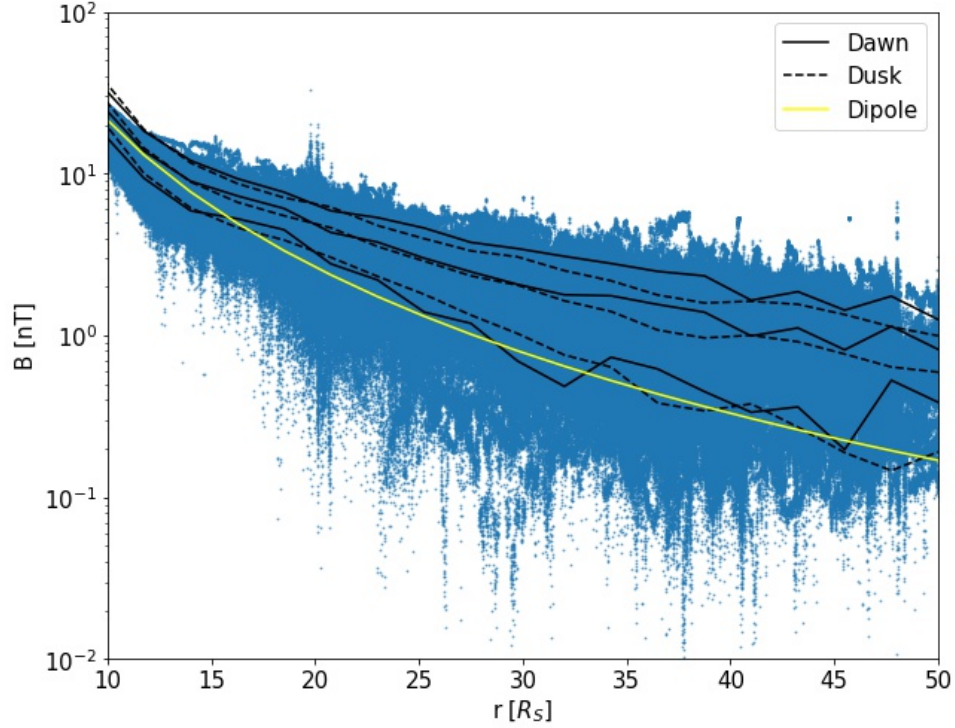


Figure 6.11: The dayside equatorial ($\pm 20^\circ$ latitude) magnetic field strength is shown in blue as a function of radial distance from the planet. The black and dashed black lines shown the magnetic field strength profiles calculated in the dawn and dusk local time sectors, respectively. The central line in both cases is the mean field strength, the upper and lower lines are the $\pm 1\sigma$ profiles. The equatorial dipole field strength [Dougherty et al., 2018] is also shown.

scale the turbulent cascade would reach in the outer magnetosphere is the gyroperiod of oxygen ions that are sourced from the moon Io. This wave-particle interaction heats the plasma and could explain the non-adiabatic temperature profile observed at Jupiter. At Saturn, von Papen et al. [2014] showed that turbulence identified in magnetic field fluctuations can contribute to the required heating rate for the increasing temperature observed.

Kaminker et al. [2017] calculated the turbulent heating rate density $q \sim$

W/m^3 of plasma throughout the Saturnian system. This turbulent heating term is proportional to magnetic field fluctuations and describes the turbulent dissipation rate from the magnetic field to the plasma. They found a quiet region between 3-9 LT with values of q tightly concentrated between 10^{-19} and $10^{-18} \text{ W}/\text{m}^3$ and an active region between 10-20 LT with the q values concentrated between 10^{-18} and $10^{-16} \text{ W}/\text{m}^3$. This average two orders of magnitude difference in q suggests turbulent heating would produce a cooler ion population at dawn compared to the pre-noon to dusk sectors.

Ng et al. [2018] presented a turbulent heating model for Jupiter that is similar to Saur [2004] but where the plasma is transported by advection (e.g. via ballooning) rather than through diffusion (e.g. via interchange motions). Neupane et al. [2021] applied this model at Saturn to show that advective turbulent heating could describe the nonadiabatic heating of W^+ ions. They found that the model well describes the outer magnetosphere observations but underestimates the temperature in the inner magnetosphere. They suggest this could be due to both inward and outward transport being important in this region. Nonetheless, the focus of the present study is the outer magnetosphere so the Ng et al. [2018] model is used for the ion temperature input in Equation 6.1. Importantly, a heating rate local time asymmetry will be included [Kaminker et al., 2017]. The Ng et al. [2018] model temperature is given by

$$T = T_0 \left(\frac{L}{L_0} \right)^{-2\beta/3} + c_1 \left(\frac{L}{L_0} \right)^{-2\beta/3} \int_{L_0}^L q(L') \frac{L'^{\alpha+2\beta/3}}{L_0^{2\beta/3}} dL', \quad (6.2)$$

where the same parameters as Neupane et al. [2021] are used, such that: $L_0 = 8R_S$ is the inner boundary radial distance chosen since at this distance the rate of radial transport times increases [Bagenal and Delamere, 2011]; T_0 is the average ion temperature at $8R_S$ found by fitting a power law to the measured ion temperature [Wilson et al., 2017] and using the model value at $L = 8R_S$; $\alpha = 2$ [Neupane et al., 2021]; β is found by fitting a power law

to the ion number density, such that $n_i \propto L^{-\beta}$ and $\beta = 4.84$ [Wilson et al., 2017]; and $c_1 = \frac{2R_S^3 2\pi m_i H}{3\dot{M} k_b}$ where $m_i = 16$ amu for W^+ ions; $H = 1.6R_S$ is the current sheet thickness [Staniland et al., 2020]; and $\dot{M} = 50$ kg is the mass transport rate [Neupane et al., 2021].

All these parameters are fixed for both local time sectors except q . The radial profile of q calculated by Neupane et al. [2021] is used, but its magnitude in each local time sector is varied, given by $q = 2.51 \times 10^i L^{-0.3}$ where $i = 16, 18$ for dusk and dawn, respectively [Kaminker et al., 2017].

The temperature profiles calculated are shown in Figure 6.12. A better fit could be achieved by varying the other model parameters. Neupane et al. [2021] found that the Ng et al. [2018] model underestimates the ion temperature [Wilson et al., 2017] in the middle magnetosphere. They suggest this could be due to the inward transport being important in this region. Figure 6.12 shows this underestimate in the middle magnetosphere. Nonetheless, the focus of this study is the temperature in the outer magnetosphere where the expected cushion region would form and where the model performs better. The model is used to estimate the effect of different heating rates in each local time sector. The specific choice of the other model parameters is not of importance to this study since they are held constant between the two local time sectors.

Inserting these into Equation 6.1, we get one-dimensional gyroradii profiles as a function of radial distance shown in Figure 6.13. At dawn the gyroradius increases from $\sim 10^1$ km in the inner magnetosphere, to 10^2 km close to the nose standoff distance, and finally to 10^3 km at the terminator. At dusk the gyroradius is larger due to the higher temperature, reaching 10^4 km at the terminator.

To calculate R_C we know that the curvature of a circle is the reciprocal of its radius. To find the curvature of a field line at Saturn in the equatorial region where the field is most disc-like, the AGA/UCL Magnetodisc Model [Achilleos et al., 2010] is employed assuming an average hot plasma index

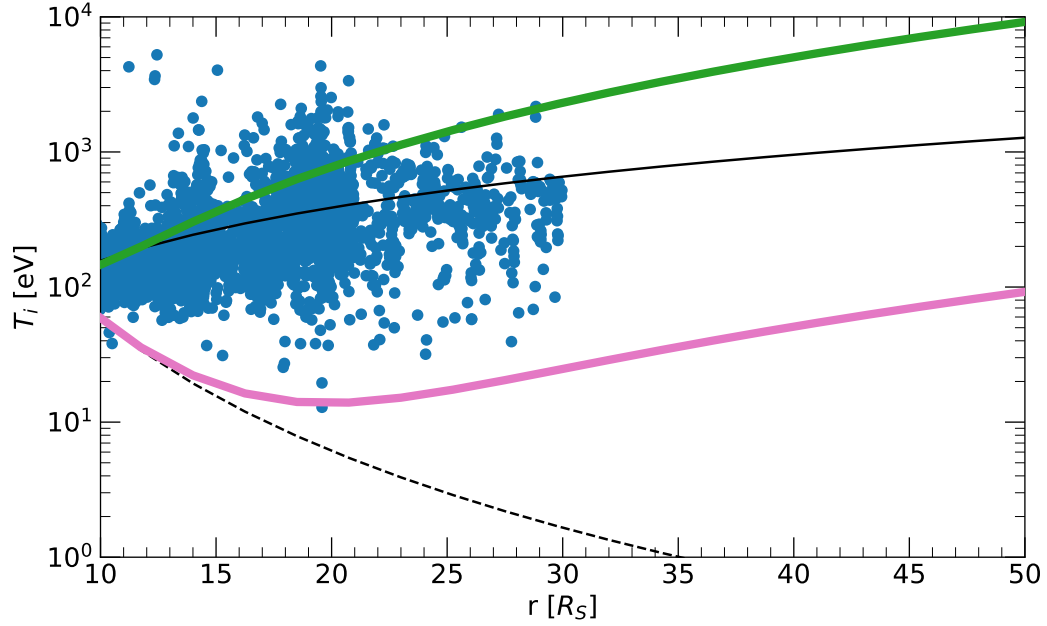


Figure 6.12: The dayside (6-18 LT) temperature of water group ions from the Wilson et al. [2017] forward fitting model is shown as a function of radial distance. The black line shows the power law fit given by $T_i = 7.9 \times r^{1.3}$ in units of eV. The thick coloured lines show the Ng et al. [2018] modelled temperature using Equation 6.2 but varying q with the green and pink lines showing the dusk and dawn ion temperatures, respectively. The dashed line shows the adiabatic temperature profile which comes from Equation 6.2 when there is no heating source.

of $K_h = 2 \times 10^6$ Pa m where K_h is essentially a measure of the ring current activity. The curvature of the field is given by

$$\kappa = \left\| \frac{dT}{ds} \right\|, \quad (6.3)$$

where T is the field tangent for some given arc length s and can be calculated from the AGA/UCL model outputs. This is converted to the radius of curvature using

$$R_C = 1/\kappa. \quad (6.4)$$

The smallest value of R_C in the middle magnetosphere of the model is $\sim 0.7R_S$ and is set as a minimum threshold for the length-scale associated with the magnetodisc geometry.

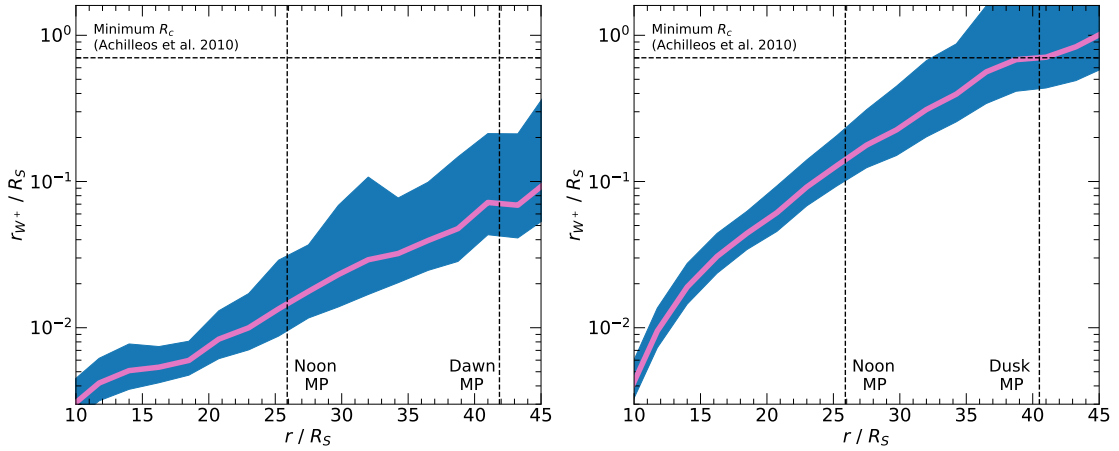


Figure 6.13: The water group ion gyroradius r_{W+} is shown as a function of radial distance for the dawn (left) and dusk (right) local time sectors. The horizontal dashed lines show the minimum expected radius of curvature. The vertical dashed lines show the average nose standoff distance for our five cushion examples and the mapped dawn and dusk terminators. The pink line shows r_{W+} calculated using the average magnetic field strength. The blue region shows r_{W+} calculated using the standard deviations of the mean magnetic field. These results show that r_{W+} approaches R_C at dusk at distances between noon and the terminator but at dawn it far less likely to. Plot from Staniland et al. [2021].

Figure 6.13 shows that at dawn the gyroradius remains smaller than the minimum expected radius of curvature associated with the magnetodisc geometry. At dusk the ion gyroradius is more likely to approach magnetodisc curvature length-scales in the outer magnetosphere primarily due to the greater heating rate density. Past this region, the MHD approximation of the magnetodisc breaks down and force balance is no longer maintained.

A sketch of this is shown in Figure 6.14. Kaminker et al. [2017] have shown that the whilst the average heating rate density measured at dusk is larger than at dawn, it is also more variable, indicative of spot heating and spatially intermittent turbulence. This could explain why the cushion region is not a systematic dusk feature and instead arises infrequently.

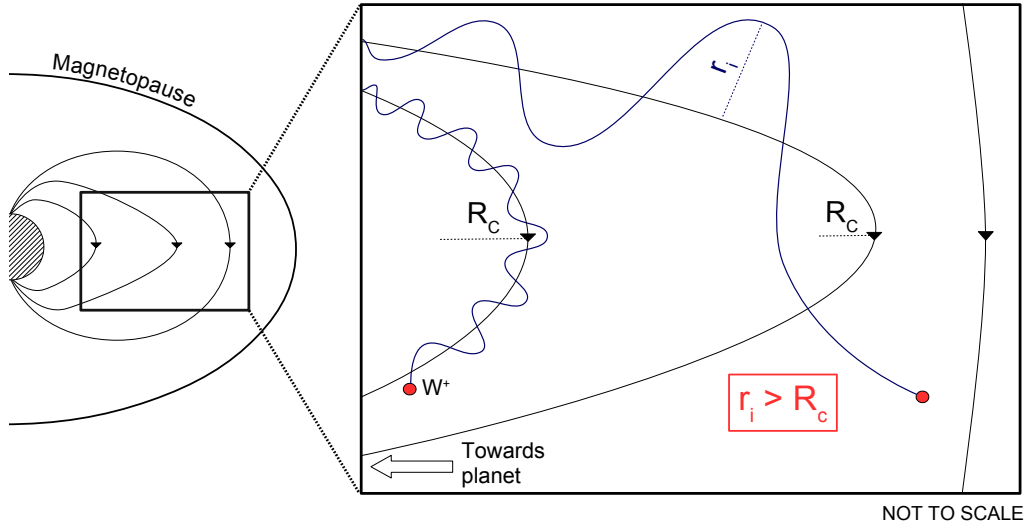


Figure 6.14: Sketch of the dayside magnetosphere in the meridional plane. The zoomed-in box shows the effect of a decreasing field line curvature and increasing particle gyroradius. Close to the planet the water group ion (shown in red) gyrates along the magnetic field. However, when the ion gyroradius r_i approaches the radius of curvature R_C it can no longer be contained by the field and can escape the disc.

Delamere et al. [2015] found evidence of mass being lost from the disc through signatures of reconnection ($B_\theta < 0$) predominantly in the sub-solar to dusk regions. They suggest a circulation pattern in the magnetodisc where mass is lost through patchy reconnection in the dusk flank rather than through large-scale tail reconnection. In our study, whilst we have observed large-scale cushion regions forming at dusk, they are rare. We suggest that the intermittent signatures of a cushion and the patchy re-

connection observed at dusk by Delamere et al. [2015] are probably more typical. As flux tubes rotate through dusk they are able to expand since the magnetopause no longer confines the field, resulting in a centrifugally driven increase in the parallel pressure of the plasma. This triggers an anisotropy ($T_{\parallel} > T_{\perp}$) that results in the disc becoming explosively unstable at dusk [Kivelson and Southwood, 2005]. There could also be a further role of the solar wind and the Dungey cycle [Dungey, 1961] in the dusk cushion formation, as well as the planetary period oscillations that thin the current sheet [e.g. Cowley et al., 2017].

At Jupiter Vogt et al. [2010] identified a statistical reconnection x-line in the post-midnight sector of the tail at distances $> 60R_J$. This clear boundary between positive and negative B_{θ} signatures compared to the patchy reconnection observed predominantly at dusk at Saturn could further highlight why the systematic cushion at Jupiter is well-described as a return flow channel following tail reconnection, but the Saturn cushion region is not. However, following the arrival of Juno at Jupiter, Gershman et al. [2018] found that there lacked a systematic dawn cushion region at Jupiter. With the progress of Juno's trajectory towards from dawn to dusk, this mission could provide the opportunity for further research into cushion region formation at Jupiter and a comparison with Saturn.

The suprathermal plasma population within the magnetosphere of Saturn could also play a role in cushion formation. These particles are more mobile and gyrate further up the magnetic field. The energetic particles and distribution of suprathermal pressure can help to maintain a quasi-dipolar field in the outer magnetosphere. At the same time, the suprathermal plasma can act to inflate the radially stretched flux tubes in the disc region. The suprathermal plasma can exert anisotropic pressure with $p_{\parallel} > p_{\perp}$ adding to the disc-like configuration of the field. This could drive a ballooning instability leading to magnetodisc break down. There is an asymmetry in the hot plasma pressure, which is larger at dusk compared to

dawn [Sergis et al., 2017, Sorba et al., 2019] that could motivate disc break down in this region and explain the dusk cushion observed.

Pulsations in the dusk ultraviolet (UV) auroral emissions have been linked with magnetodisc reconnection [Bader et al., 2019]. At dawn the aurora is everpresent and characterised by a thin arc whilst at dusk the UV aurora is patchy and scattered [Bader et al., 2020]. These phenomena highlight the quieter dawn magnetodisc that maps to the aurora via field-aligned currents compared to the active and more variable dusk magnetodisc and cushion that generate these structures.

6.5 Conclusions

Based on analysis using magnetometer data from the early Cassini mission, a quasi-dipolar cushion region in the outer dayside magnetosphere was not identified at Saturn [Went et al., 2011b]. Now that the mission is complete the entire magnetometer dataset has been surveyed to search for evidence of a cushion region forming. Based on two criteria regarding the magnetic field structure five examples of a cushion region at Saturn have been identified, four of which are at dusk, showing that this phenomenon is rare. These results are in contrast with the current interpretation of a cushion that suggests it is a return flow channel of mass depleted flux tubes following tail reconnection.

This study argues that due to a local time asymmetry in the heating of the plasma and the expansion of the field as the plasma moves through the afternoon sector the disc at dusk can break down, allowing for a cushion region to form in this local time sector. It is also likely that energetic particles will contribute to the formation of the cushion region, as well as the solar wind and the ubiquitous PPOs.

The difference in local time distribution coupled with the rarity of cushion observations at Saturn reveals a key difference to Jupiter. At Jupiter,

the cushion region forms at dawn and is populated by mass-depleted flux tubes that have convected from the nightside following large-scale tail reconnection. The sporadic nature of the Saturnian cushion region and dusk observations are at odds with the observations at Jupiter. These results have significant implications regarding mass transport, dynamics and global structure at Saturn and how these differ to Jupiter.

Chapter 7

Conclusions and Future Work

The Cassini-Huygens mission to Saturn proved a landmark in space exploration. The spacecraft surveyed a large portion of the near-space environment surrounding Saturn and this has enabled a greater understanding of this system. The mission delved into many questions, including the structure of the intrinsic field [Dougherty et al., 2018], the composition of its atmosphere [e.g. Flasar et al., 2005, Brown et al., 2020] and the dynamics of its rings [Cuzzi et al., 2009]. Whilst the analyses of the Cassini magnetic field data undertaken so far have perhaps answered the key mission objectives, there are likely questions yet to be uncovered. New results will continue to be produced from this vast dataset for years to come.

This thesis has aimed to contribute to our understanding of Saturnian magnetosphere and to utilise the entire Cassini orbital dataset now the mission has recently ended. The question this thesis has focussed on is: *how does the magnetodisc current sheet shape the large-scale magnetic field structure of Saturn?* It is the hope that the research presented here will go towards answering this question. The remainder of this chapter will summarise the key results presented in this thesis and how they contribute to our understanding of the structure of the Saturnian magnetosphere. Some possibilities for future work will also be discussed in the hope that it can guide new

research.

7.1 Chapter 4: Saturnian stress index

This chapter presented a global stress index for Saturn to track when the system was expanded, compressed, or near its ground state [Staniland et al., 2018]. The aim was to provide a method for detecting global changes in the Saturnian magnetosphere and to reveal how often significant perturbations to the system occur. At Earth, the *Dst* index provides a similar function.

An underlying local time asymmetry was observed where the field is more compressed at dusk and expanded at dawn. Once a local time ground state was subtracted a stress index was determined for each Cassini revolution. The results showed that the system remained close to its ground state for a significant portion of the Cassini mission, but large-scale deviations were observed. A key finding was that 38% of the 111 orbits passed the current sheet when it was not in steady-state. These results show the timescales by which the system undergoes reconfiguration and how often these large events occur.

Possible driving mechanisms for stress index variability were discussed. Some tentative evidence of solar wind control and sunspot correlation with system size was found, but it was not statistically significant. These results show the interaction between internal and external factors in driving large-scale changes in stress. This catalogue of stress indexes allows us to track the global structure of the Saturnian magnetosphere over long time-scales and between Cassini orbits. It also provides the opportunity to compare the global state of the system with other measured phenomena.

7.2 Chapter 5: Current Sheet Thickness

This chapter presented a study of the current sheet thickness and its variability [Staniland et al., 2020]. The aim was to study how the vertical structure of the current sheet changes due to different drivers, including the solar wind and the PPOs, and to understand whether one of these dominates.

The results were that the current sheet is thicker close to the planet on the nightside compared to the dayside, consistent with the presence of a noon-midnight electric field in the inner magnetosphere [Thomsen et al., 2012]. It was found that the current sheet gets thinner with distance from the planet on the nightside, but remains approximately constant on the dayside, reflecting the solar wind confinement of the dayside magnetic field. Some correlation between thickness modulations and PPO phases were identified that were consistent with expectations, but there was evidence for other sources of variability. These results highlight the interplay between the PPOs, the solar wind and the internally sourced plasma population at Saturn in modifying the thickness of the current sheet.

The key result of this study was to provide values for the thickness of the current sheet and constraints on its variability. These are essential for modelling the current sheet and will be pertinent for future analysis of the Cassini mission data since the current sheet is one of the dominant external magnetic field contributors. The results reveal the vertical structure of the Saturnian system is highly asymmetric and responds to multiple different drivers, with the largest variation due to radial distance from the planet.

7.3 Chapter 6: The Cushion Region

This chapter considered the limits of the magnetodisc structure that is observed at Saturn and where it might break down [Staniland et al., 2021].

The cushion region, a quasi-dipolar region in the outer dayside magnetosphere, has been observed at Jupiter but not at Saturn, despite their similarities. The aim of this chapter was to identify, using the complete Cassini dataset, if there is a cushion region at Saturn.

The results were that cushion region formation at Saturn is rare with only five examples identified. An unexpected result was that the majority of these were at dusk, rather than dawn as is found at Jupiter. These suggest that a new formation mechanism is required to explain these observations as they cannot be understood in terms of tail reconnection and return flow. It was suggested that asymmetric heating of the equatorial plasma [Kaminker et al., 2017] and the expanding magnetic field configuration through dusk could trigger disc instabilities.

These results highlight a key difference between the Saturn and Jupiter systems. Both magnetospheres are rotationally-driven and have internal plasma sources that modify their global structures. However, the rare cushion region examples found and evidence of patchy reconnection at Saturn [Delamere et al., 2015] compared to the persistent cushion region [Went et al., 2011b] and statistical x-line across the Jovian tail [Vogt et al., 2010] shows that mass transport and loss mechanisms differ between these systems. Whilst the Saturn system is often described as being between Jupiter and the Earth in terms of dynamics and structure, the results presented here suggest that this is perhaps an oversimplified description.

7.4 Open Questions

The work in this thesis has explored the large-scale structure of the Saturnian magnetosphere, focussing primarily on the impact of Enceladus as an internal plasma and how this gives rise to the magnetodisc. Whilst the work presented here has contributed towards our understanding of this effect it has also raised some new questions. A brief, and by no means

exhaustive, outline of some of these questions is given here that could provide direction for future work.

In Chapter 4, a global stress index was calculated throughout the Cassini era. Whilst a comparison with propagated solar wind data was presented, it would be of interest to explore other possible sources of stress index variability. For instance, the variable outgassing of Enceladus [Smith et al., 2010] was not considered. Periods of greater neutral, and in turn plasma, production could affect the disc force balance. This could quantify the importance of a variable internal plasma source in modifying the global structure.

In Chapter 5, the current sheet thickness and variability was determined. Further research into the local plasma environments could be particularly revealing, for instance by calculating the thickness as a function of plasma kinetic scales. This would be important for discussions regarding current sheet reconnection. In addition, due to Cassini trajectory constraints the dawn and dusk current sheet thickness was not determined. Further exploration of the current sheet thickness in these local time sectors using other methods could lead to a complete global profile of the current sheet thickness at Saturn. This would be useful for comparison with Jupiter, where the current sheet is significantly thicker at dusk compared to dawn.

In Chapter 6, the first evidence of a sustained cushion region forming at Saturn was found. One mechanism was suggested for the unexpected dusk observations. Future work could consider additional mechanisms for forming the cushion region at Saturn. For instance, the PPOs are known to thin the current sheet and thus we might expect some PPO control of cushion formation. The role of the solar wind and the suprathermal plasma populations could also be considered. Further analyses using data from the Cassini plasma instruments would provide greater understanding of the plasma environment in the cushion region. In addition, the recent discovery using Juno data of an example of no cushion

region at Jupiter's dawn flank [Gershman et al., 2018] shows that further research must be undertaken to understand cushion region formation in rotationally-dominated magnetospheres. Finally, the non-adiabatic heating of plasma observed at Saturn that could explain the cushion region also provides particular insight and discussion with regards to plasma heating and processes in the outer regions of other magnetospheres.

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