

MAG



The Magnetometer (MAG) experiment/instrument onboard the Cassini spacecraft consisted of two magnetometers that measured the magnetic field in and near Saturn's magnetosphere. The **science objectives** of MAG were to determine Saturn's internal magnetic field, map the magnetospheric magnetic field, and characterize the magnetospheric interaction with Titan and the icy satellites. MAG was the first instrument to detect an unusual signature from Enceladus that foreshadowed the Enceladus plume.

MAG consisted of a three-axis Flux-Gate Magnetometer (FGM) and a Vector/Scalar Helium Magnetometer (V/SHM) designed to record the direction and strength of magnetic fields in the Saturn system. On the Cassini spacecraft, the FGM was located midway out on the 11-meter (36-foot) magnetometer boom, and the V/SHM was located at the end of the boom.

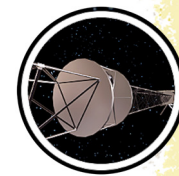


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EXECUTIVE SUMMARY

The key science results from the Cassini MAG team include, but are not restricted to:

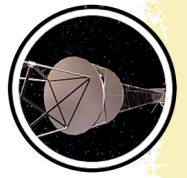
- Discovery of the atmosphere of Enceladus via its magnetospheric interaction.
- Confirmation of the extreme axisymmetry of Saturn's magnetic field (this work, as well as an attempt to pin down the internal rotation rate, continues with analysis of the Grand Finale data set).
- Discovery of low-latitude, intra-D-ring field-aligned current system at Saturn.
- Mission-long magnetic field measurements of Saturn's planetary period oscillations (PPOs) demonstrate strong, but not simple, seasonal control.
- Saturn's atmosphere-ionosphere-magnetosphere coupling current system consists of two interlinked components.
- Much better understanding of Saturn magnetospheric dynamics.
- MAG-led discovery of Titan's magnetic memory.
- MAG-led discovery of Saturn's two-state magnetosphere.
- MAG/ Magnetospheric Imaging Instrument (MIMI) discovery of the internal inflation for Saturn's magnetosphere.

The key outstanding questions from Cassini MAG data and science output include:

- What are the implications of the extremely axisymmetric planetary magnetic field for the internal structure and dynamics of Saturn?
- What is the dynamo process generating this unique planetary field?
- How are the PPOs driven in the atmosphere/ionosphere of Saturn?
- Understand the variety of currents observed during the periapse periods of the Grand Finale orbits and their implications for coupling between the atmosphere-ionosphere-magnetosphere-rings.

MAG INSTRUMENT SUMMARY

The Cassini dual technique MAG consisted of a FGM and a V/SHM capable of operating in scalar mode. The instrument was intended to measure small changes in fields spanning four orders of magnitude with extremely high sensitivity. This was achieved in part by mounting the sensors on an 11-meter spacecraft boom, the V/SHM at the end of the boom, the FGM halfway along it. The FGM was based on three single-axis ring core fluxgate sensors mounted orthogonally on a machinable glass ceramic block. In each sensor, a drive coil was wound around a high permeability ring core, which was completely enclosed in a sense winding. The drive coil was driven by a square wave that was used to generate a magnetic field driving the core into saturation twice per cycle.



The presence of an ambient magnetic field component parallel to the axis of the sense coil caused the saturation of the core to become asymmetrical. This induced a second harmonic of the drive frequency in the sense coil, which was proportional to the magnitude of the magnetic field component along that axis. The V/SHM was based on field-dependent light absorption (the Zeeman Effect) and optical pumping to sense the magnetic field. Helium in an absorption cell was excited by a radio frequency discharge to maintain a population of metastable long-lived atoms. Infrared radiation at 1,083 nm from a helium lamp passed through a circular polarizer and the cell to an infrared detector. The absorption of the helium in the cell was dependent on the ambient magnetic field direction. The normal data rate for the instrument was 32 vectors/second with the ability to take data in a burst mode at 64 vectors/second. Magnetic field information was needed by other investigations on the spacecraft and to this end, magnetic field data were made available to Magnetospheres and Plasma Science (MAPS) [Blanc et al. 2002] onboard users every second.

Calibration plans had to be changed a year after arrival at Saturn when the V/SHM stopped operating with regular calibration rolls around two separate axes required for the rest of the mission lifetime to enable calibration of the single FGM and hence resolution of the science objectives of the MAG team. MAG is described in detail in Dougherty et al. [2004]; Kellock et al. [1996]; Smith et al. [2001].

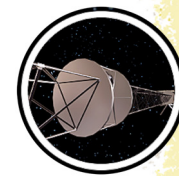
KEY OBJECTIVES FOR MAG

The key science objectives for MAG, as described in the Dougherty et al. [2004] paper, are listed below and divided into two main areas, focusing on the planet and its magnetosphere and on Titan. The third area examining the icy satellites of Saturn gained much more importance of course after the initial observations during the first four years of the mission and the water vapor plume discovery [Dougherty et al. 2006] at Enceladus.

All of the MAG objectives have been achieved, with only the 3-D global field model remaining until all of the end-of-mission data has been completely analyzed and modelled.

Saturn

- Resolve the internal planetary magnetic field to at least fourth order.
- Establish relative contributions to electromagnetic and mechanical stress balance.
- Identify the energy sources for dynamical processes.
- Understand the coupling that occurs between the magnetosphere and ionosphere.
- Characterize the phenomena of the distant dayside/flank planetary environment.
- Survey satellite/dust/ring/torus electromagnetic interactions.
- Determine the tail structure and dynamic processes.



- Provide a three-dimensional (3-D) global model of the magnetospheric magnetic field.

Titan

- Determine the magnetic state of the body and conditions of the atmosphere.
- Characterize and model the Titan electromagnetic environment.
- Interpret and model all Titan-plasma flow interactions and the variation of the Titan-magnetosphere interaction with respect to the Titan orbital phase.
- Determine the nature of the low-frequency waves in the near-Titan plasma environment.

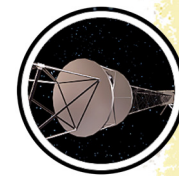
Saturnian satellites other than Titan

- Probe the magnetic state and plasma environment of the Saturnian satellites to the extent possible within the limitation of the chosen trajectory.

All of the above objectives have been achieved, with the exception of the 3-D global field model, which still requires work and will be achieved once all of the end-of-mission data has been completely analyzed and modelled.

Key Objectives for MAG from Announcement of Opportunity (AO) and Cassini Solstice Mission (CSM)

- R_AO5—Ring Magnetosphere-Ionosphere Interactions. Study interactions between the rings and Saturn's magnetosphere, ionosphere, and atmosphere.
- M_AO1—Determine the configuration of the nearly axially symmetric magnetic field and its relation to the modulation of Saturn kilometric radiation (SKR).
- M_AO2—Magnetosphere Charged Particles. Determine current systems, composition, sources, and sinks of magnetosphere charged particles.
- M_AO03—Investigate wave-particle interactions and dynamics of the dayside magnetosphere and the magnetotail of Saturn and their interactions with the solar wind, the satellites, and the rings.
- M_AO4—Magnetosphere and Solar Interactions with Titan. Study the effect of Titan's interaction with the solar wind and magnetospheric plasma.
- M_AO5—Plasma Interactions with Titan's Atmosphere and Ionosphere. Investigate interactions of Titan's atmosphere and exosphere with the surrounding plasma.
- I_AO5—Icy Satellite Magnetosphere and Ring Interactions. Investigate interactions with the magnetosphere and ring systems and possible gas injections into the magnetosphere.



- J_AO3—Explore the dusk side of the magnetosphere and intermediate regions of the magnetotail unvisited by previous spacecraft.
- C_AO2—Investigate the behavior of the solar wind during solar minimum, for comparison with earlier Galileo and Ulysses measurements.
- S_AO3—Saturn Interior Structure and Rotation. Infer the internal structure and rotation of the deep atmosphere.
- S_AO4—Saturn Ionosphere-Magnetosphere Interaction. Study the diurnal variations and magnetic control of the ionosphere of Saturn.
- T_AO4—Determine the physical state, topography, and composition of the surface; infer the internal structure of the satellite.
- IN1a—Determine the presence of an ocean at Enceladus as inferred from induced magnetic field and plume composition, search for possible anomalies in the internal structure of Enceladus as associated with plume sources, and constrain the mechanisms driving the endogenic activity by in situ observations and remote sensing.
- IN1c—Determine whether Dione exhibits evidence for low-level activity, now or in recent geological time.
- IN2b—Determine whether Tethys contributes to the E-ring and the magnetospheric ion and neutral population.
- SC2a—Observe the magnetosphere, ionosphere, and aurora as they change on all time scales—minutes to years—and are affected by seasonal and solar cycle forcing.
- SN1a—Determine Saturn’s rotation rate and internal structure despite the planetary magnetic field’s unexpected high degree of axisymmetry.
- MC1a—Determine the temporal variability of Enceladus’ plumes.
- MC1b—Observe Saturn’s magnetosphere over a solar cycle, from one solar minimum to the next.
- MC2a—Observe seasonal variation of Titan’s ionosphere from one solstice to the next.
- MN1a—Determine the dynamics of Saturn’s magnetotail.
- MN1b—Conduct in situ and remote sensing studies of Saturn’s ionosphere and inner radiation belt.
- MN1c—Investigate magnetospheric periodicities, their coupling to the ionosphere, and how the SKR periods are imposed from close to the planet (3–5 R_s) out to the deep tail.
- MN2a—Determine the coupling between Saturn’s rings and ionosphere.



- TC2a—Observe Titan’s plasma interaction as it goes from south to north of Saturn’s solar-wind-warped magnetodisk from one solstice to the next.
- TN1b—Determine internal and crustal structure: liquid mantle, crustal mass distribution, rotational state of the surface with time, intrinsic and/or internal induced magnetic field.

MAG SCIENCE ASSESSMENT

Table MAG-1. AO and TM objectives are paired with MAG science objectives.

Fully/Mostly Accomplished: ■		Partially Accomplished: ■	Not Accomplished: ■
MAG Science Objectives Characterize the following:	AO and TM Science Objectives	MAG Science Assessment	Comments, if yellow (partially fulfilled)
Planetary magnetic field	S_AO3, M_AO1, SN1a		
Magnetospheric structure and dynamics			
Magnetospheric periodicities	MN1c, SC2a		
Saturn magnetosphere-ionosphere coupling	R_AO5, S_AO4, MN1b, MN1c, MN2a		
Magnetospheric current systems	M_AO2		
Magnetosphere—dayside, middle magnetosphere, magnetotail, solar wind interaction	M_AO3, MN1a		
Seasonal and solar wind variation	SC2a, MC1b		
Ring-magnetosphere interactions	R_AO5, MN2a		
Titan			
Titan and magnetospheric interaction	M_AO4, M_AO5, T_AO4, MC2a, TC2a, TN1b		
Icy satellites			
Enceladus internal structure and activity	MC1a, IN1a		
Moon-magnetosphere interaction	I_AO5		
Icy satellite activity, Dione, Tethys	IN1c, IN2b		
Non-Saturn science			
Jovian magnetosphere	J_AO3		
Properties of the solar wind	C_AO2		

MAG SATURN SYSTEM SCIENCE RESULTS

Saturn’s Bow Shock

The distant apoapsis orbits by the Cassini spacecraft around Saturn over many years enabled hundreds of bow shock crossings. This allowed for thorough analyses from modelling the (3-D) shape and predicting the location of the boundary to investigating the microphysics of high Mach



number shocks. The magnetometer instrument proved indispensable in advancing our understanding of Saturn's bow shock. Below are the highlights:

Detailed characterization of Saturn's bow shock

Masters et al. [2008a] and Went et al. [2011a] developed the most comprehensive semi-empirical model of Saturn's dayside bow shock. The average 3-D shape of the boundary was constructed and equations relating the response of the subsolar point to variations in solar wind dynamic pressure were derived. The identification of bow shock crossings was most reliably and straightforwardly achieved using MAG. The classic signature for an inbound crossing, i.e., from the solar wind to the magnetosheath, was an abrupt rise from a low and steady to a large (~4x) and turbulent magnetic field strength. The reverse was the case for an outbound crossing.

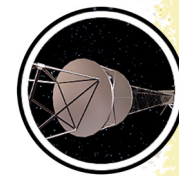
The magnetometer instrument proved indispensable in advancing our understanding of Saturn's bow shock.

Achilleos et al. [2006] presented magnetic field signatures of some of the earliest crossings in the mission. Their results showed clearly defined overshoot and foot signatures that are typical of quasi-perpendicular shocks. This is one of two configurations of shocks in magnetized plasmas (the other being quasi-parallel) where the local normal to the shock surface makes an angle of $>45^\circ$ to the interplanetary magnetic field. This is by virtue of the Parker spiral structure of the interplanetary magnetic field (IMF) at 10 AU, where the magnetic fields met the bow shock with very large azimuthal

components. Sulaiman et al. [2016] characterized Saturn's bow shock using the largest sample of crossings to date. With the utility of the aforementioned models, they showed Saturn's dayside bow shock was in the quasi-perpendicular configuration for a large majority of the time. Further, they estimated the Alfvén Mach numbers (a measure of the shock's strength) for all crossings to show that Saturn's bow shock spans over a very wide range of parameter space. The bow shock was found to exhibit characteristics akin to both terrestrial and astrophysical regimes. This laid the foundation for further detailed studies specific to astrophysical shocks (e.g., surrounding young supernova remnants), providing an in situ insight into such regimes, which were otherwise studied using remote observations and/or simulations. Masters et al. [2008b, 2009a] presented a survey of hot flow anomalies at Saturn's bow shock, all of which were associated with energization of solar wind electrons. Having been a well-established phenomenon at the Earth's bow shock, these works underlined hot flow anomalies as a solar system-wide phenomenon.

Dissipation at high Mach number shocks

In the presence of an obstacle, shock waves in a neutral gas efficiently dissipate the supersonic flow to subsonic through the action of collisions. In space plasmas, however, shocks cannot rely on collisions to adequately dissipate the flow since the collisional mean free path is many orders of magnitude larger than the shock's width. Here, electromagnetic forces play important roles to compensate for the additional dissipation required. Their roles are well understood for modest Mach



numbers (e.g., 2–10). However, the dissipation becomes more complicated at larger Mach numbers since additional kinetic processes, namely ion reflection and reformation, come into play to complete the process. Fortunately, such high Mach number phenomena were explored using the Cassini magnetometer dataset. Sulaiman et al. [2015] showed evidence for the timescales of ions reflection at a shock undergoing reformation to be 0.3 times the upstream gyroperiod. This was in excellent agreement with what had been theorized.

Masters et al. [2011a] investigated the Mach number dependence of electron heating across a bow shock. Their work presented a positive correlation between the electron temperature increase across the shock and kinetic energy of an incident proton, where electron heating accounts for ~3%–7% of the incident ram energy. Further, they confirmed that the trend of the decreasing percentage with increasing Alfvén Mach number continues into the poorly explored high Mach number regime, up to ~150. Masters et al. [2013a] compared observations of overshoots between Mercury’s and Saturn’s bow shocks, both of which represent drastically different Mach numbers in parameter space. They showed, on average, the overshoots at Saturn’s bow shock were much higher than those observed at Mercury’s. This supported the larger role of particle dynamics at higher Mach numbers. The low Mach number class of shocks were also explored. Sulaiman et al. [2017a] examined the dispersive properties of Saturn’s bow shock through the identification of electromagnetic precursors consistent with whistler waves. These waves were believed to play a limited role in the dissipation process and were found to be right-handed circularly polarized with a frequency of 0.2–0.4 Hz in the spacecraft frame.

Electron acceleration at high Mach number shocks

Collisionless shock waves are also known to be efficient particle accelerators. It is widely believed that a large proportion of cosmic rays originate from energetic charged particles accelerated at collisionless shocks associated with supernova explosions in our galaxy. Masters et al. [2013b] confirmed, for the first time, electron acceleration up to relativistic energies at an unusually strong Saturn bow shock under a quasi-perpendicular configuration. This contradicted previous knowledge purporting a magnetic dependence on this phenomenon. Further works by Masters et al. [2016] and Masters et al. [2017] provided the full picture of suprathermal electrons at Saturn’s bow shock. They showed results that are consistent with the theory in which the injection of thermal electrons into an acceleration process is possible for all magnetic field configurations at high Mach numbers.

Additionally, MAG provided important observations to study the properties of Saturn’s foreshock, the portion of the upstream solar wind magnetically connected to Saturn’s bow shock. An in-depth characterization of the waves originating from solar wind-charged particles backstreaming from the shock [Bertucci et al. 2007a] was followed by the identification of the spatial extent of the region where these waves are observed [Andres et al. 2013] with a technique that was also successfully applied to the Earth’s foreshock [Andres et al. 2015].



Saturn's Magnetosheath

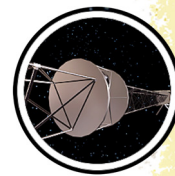
Long-term sampling of Saturn's magnetosheath by Cassini afforded the most complete coverage of this intermediary region between the unshocked solar wind and Saturn's magnetosphere. A relatively high Alfvén Mach number solar wind and a polar-flattened magnetosphere make Saturn's magnetosheath both physically and geometrically distinct from the Earth's. Fast rotating gas giants, such as Saturn, are bulged along the equator and flattened along the poles owing to their embedded plasma disks and for this reason, Sulaiman et al. [2014] showed that the magnetic structure of Saturn's magnetosheath significantly deviated from axisymmetry. Their results showed large northward/southward components in the magnetic field despite the prevailing Parker spiral configuration being largely in the equatorial plane.

Sulaiman et al. [2017b] addressed the impact of nonaxisymmetry with the aid of magneto-hydrodynamic (MHD) simulations. They showed that Saturn's polar-flattened magnetosphere channels ~20% more flow over the poles than around the flanks at the terminator. They further showed the pressure gradient force is the primary driver accelerating the magnetosheath plasma. This is by virtue of the high- β plasma and, in turn, the high Mach number bow shock. This translated into larger pressure gradients over shorter paths (over poles) compared to longer paths (around flanks), which explained the net torque on magnetic field lines to produce the large northward/southward components. These results are anticipated to provide a more accurate insight into the global conditions upstream of Saturn and the outer planets.

Saturn's Magnetopause

Data taken by MAG at the magnetopause boundary of Saturn's giant magnetosphere have allowed us to examine the ways in which energy can be transferred into and out of near-Saturn space. Understanding this is crucial for revealing the dynamics of the coupled planetary system of magnetosphere, moons, rings, and atmosphere.

A good understanding of the geometry of the magnetopause, and how its position changes with the pressure of the solar wind, is important for characterizing the distant dayside magnetosphere and in developing a 3-D global model of the magnetospheric magnetic field. Arridge et al. [2006] used early measurements of the magnetopause from Cassini/MAG, combined with measurements from Voyager 1 and 2, and Pioneer 11, to develop a new model of Saturn's magnetopause. This study employed a new mathematical formulation, borrowed from studies of the terrestrial magnetosphere, and a new modelling methodology. This revealed that Saturn's magnetosphere was more compressible than previously thought: more compressible than Earth's magnetosphere, but less than that of Jupiter. This was confirmed and enhanced in further studies using larger datasets from Cassini/MAG [Kanani et al. 2010; Pilkington et al. 2015a]. In a study by Achilleos et al. [2008], the MAG team analyzed some of the early orbits and the points along those orbits where the spacecraft crossed the magnetopause. By analyzing the distribution of the magnetopause crossings, we concluded that the size of the magnetosphere was certainly being controlled by the dynamic pressure of the solar wind upstream of the planet, but that there was also



evidence for an additional influence, probably due to a process internal to the magnetosphere. The system preferentially spent most of the time in one of two states, characterized by subsolar magnetopause distances near ~ 22 and ~ 27 Saturn radii.

A study some years later [Pilkington et al. 2015b] built upon this work by constructing an up-to-date empirical model of Saturn's magnetopause, based on an extensive set of magnetopause crossings observed by the spacecraft. We found that we could not satisfactorily fit these crossings in their entirety by assuming a system whose size responded only to solar wind pressure. By separating the crossings into subsets based on additional plasma data from the MIMI instrument, we were able to demonstrate that Saturn's magnetosphere plausibly made transitions between states that were plasma-light and plasma-loaded, this form of internal control exerting additional influence on the magnetopause size. The work of Pilkington et al. [2015b] represented a natural progression from an earlier version of the Saturn magnetopause model developed by Arridge et al. [2006], based on a necessarily more limited dataset from several years earlier in the mission.

The structure of the magnetopause boundary itself provides information about the processes at work in this region of Saturn's space environment. MAG data have shown that the magnetopause current layer itself is typically in motion at speeds of order 100 km s^{-1} [Masters et al. 2011b]. This very high speed is considerably faster than that of the spacecraft during magnetopause encounters (a few km s^{-1}). The data also provide the first clear evidence for the existence of a boundary layer of mixed plasma immediately inside the magnetopause [Masters 2011a]. This low-latitude boundary layer is particularly important because it is the direct result of the mass and energy transport that we wish to understand. Magnetic field measurements have played a crucial role in determining that the typical thickness of the layer is approximately 1 Saturn radius ($\sim 60,000 \text{ km}$).

The observed variability in low-latitude boundary layer properties between spacecraft crossings of the near-magnetopause region led to a number of surprises. Firstly, the basic thermal electron structure of the layer is significantly variable—a phenomenon not reported in the context of Earth's magnetosphere, and yet to be explained [Masters et al. 2011c]. Secondly, the thickness of the layer itself shows no clear response to the direction of the Sun's interplanetary magnetic field in the vicinity of Saturn, in stark contrast with the behavior of the equivalent region of Earth's magnetosphere [Masters et al. 2011b]. The latter of these two unexpected results can help us to reveal the nature of a particular boundary process.

Magnetic reconnection is a fundamental process that can operate at a current sheet. It results in the release of energy stored in the local magnetic field, leading to acceleration of charged particles and allowing the direct transfer of mass and energy across an otherwise closed boundary. While evidence for the known operation of reconnection at Saturn's magnetopause has been sparse, MAG observations have formed the basis of important assessments that have broad implications. The first such assessment demonstrated that conditions at the magnetopause boundary of Saturn's magnetosphere are dramatically unlike those at Earth's magnetopause. As a result, reconnection at Saturn's magnetopause should be more restricted to regions where magnetic field lines adjacent to the boundary are locally anti-parallel to each other [Masters 2012a].



This Cassini result led to a shift in how we think about the solar wind-magnetosphere interaction at Saturn, with implications for other magnetized planets.

Understanding the ways in which energy can be transferred into and out of near-Saturn space is crucial for revealing the dynamics of the coupled planetary system of magnetosphere, moons, rings, and atmosphere.

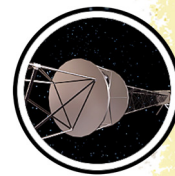
MAG data has also shown that when reconnection operates at Saturn's magnetopause it likely does so at a speed that is far slower than that associated with reconnection in environments closer to the Sun—for example, the solar corona, the solar wind, Earth's magnetopause, Earth's magnetotail [Masters et al. 2014a]. The reason for this is the way that solar wind properties change as the plasma moves away from the Sun. The Alfvén speed,

which dictates the speed of reconnection, drops with heliocentric distance, producing a relatively slow reconnection process at Saturn's magnetopause and consistent with the lack of evidence for rapid boundary layer response discussed above. This result directly contributed to further work that showed that driving of Saturn's magnetosphere by global magnetopause reconnection is rarely strong enough to compete with the internal driving of the system that results from the combination of fast planetary rotation and plasma production due to the plumes of Enceladus [Masters 2015].

A search for reconnection signatures at the Saturnian magnetopause from 10:00 to 14:00 Saturn local time (SLT) was carried out. We found brief intervals during which the normal component of the magnetic field across the magnetopause becomes significantly enhanced for typically 1 to 10 minutes. Through these magnetic bridges, the magnetosphere is connected to the magnetosheath. To determine if the magnetic reconnection leads to a measurable transfer of magnetic flux from the dayside, we checked the location of the magnetopause standoff distance for both northward and southward magnetosheath field. We found no obvious dependence of the distance on the direction of the magnetosheath field, indicating that dayside reconnection does not play a significant role in Saturnian magnetospheric dynamics [Lai et al. 2012].

The other important mechanism by which solar wind energy can enter a planetary magnetosphere is via a viscous-like interaction. This is underpinned by another fundamental process: Growth of the Kelvin-Helmholtz (K-H) instability. Where there are large plasma flow shears across a magnetopause this instability can lead to the evolution of small boundary perturbations in to gentle waves and eventually in to large, rolled-up vortices. The first evidence for magnetopause surface waves from Cassini came in the form of normals to the boundary determined from magnetic field observations that exhibited an oscillation in a preferred direction from one magnetopause crossing to the next [Masters et al. 2009b]. The direction of wave propagation (direction of boundary normal oscillation) was controlled by the local direction of the magnetic field inside the boundary, consistent with K-H-driven waves.

Extension of this initial study to consider hundreds of magnetopause crossings over a period of years subsequently revealed the bigger picture [Masters et al. 2012a]. Such waves are



ubiquitous, present at approximately half of all magnetopause encounters made by Cassini. Further evidence of the influence of adjacent magnetic fields on the wave propagation direction and a dawn-dusk difference in typical wave period demonstrated that growth of the K-H instability is one of the major drivers of these waves and, potentially, the dominant driver.

Perhaps the most compelling evidence for K-H instability at Saturn's magnetopause is the reported evidence that the spacecraft flew through a K-H-driven plasma vortex on the magnetopause in December 2004 [Masters et al. 2010]. Surprisingly, this vortex encounter coincided with detection of electrons with energies exceeding ~ 20 keV. This unexpected feature led Cassini scientists to speculate that there may be electrodynamic coupling between boundary vortices and Saturn's upper atmosphere, potentially producing some of the spot-like features regularly observed in the sources of planetary auroral emissions.

Similar to many topics, Cassini has revolutionized our understanding of how the solar wind influences Saturn's giant magnetosphere, where magnetic field observations are an essential element. Many questions have been answered, with a number of unexpected results. Cassini has made us redefine major open questions, to be addressed by future missions. An important open question relevant for this topic in the post-Cassini era is: Does the solar wind primarily interact with Saturn's magnetosphere through K-H instability?

Saturn's Magnetosphere

Saturn's cusp

At Earth, the solar wind is the primary energy source that can drive dynamical processes in the magnetosphere, and it is also a primary source of plasma. Before Cassini's arrival, it was not clear what role the solar wind played in driving the Saturnian magnetosphere, and so understanding the coupling between the solar wind and the magnetosphere, characterizing the phenomena of the distant dayside/flank planetary environment was an important goal. This included studying viscous and magnetic reconnection processes at the magnetopause. Flux transfer events are a signature of dayside magnetic reconnection at Earth, Mercury, and Jupiter, and consist of a rope of magnetic flux and plasma peeling away from the magnetopause. Jasinski et al. [2016] presented an example of a flux transfer event at Saturn (the only one) and showed that this single event made a fairly small contribution ($<10\%$) to the magnetic flux transport budget, although it was not clear how typical this event was, and if they are more prevalent at locations on the magnetopause not sampled by Cassini.

At higher latitudes, a region known as the cusp maps to a very wide region of the magnetopause and so is ideal for remote monitoring of the magnetopause for reconnection signatures, revealing coupling between the solar wind and the magnetosphere. Cassini's inclined orbits during 2007/2008 and 2013/2014 were ideal to study this coupling process in plasma—Cassini Plasma Spectrometer (CAPS)—and the magnetic field—MAG. Some of the early inclined orbits in early 2007 showed evidence of solar wind plasma gaining entry into the magnetosphere



[Arridge et al. 2016a]. This work showed evidence for movement of the cusp region in phase with magnetospheric (so-called planetary-period) oscillations, indicating the presence of current systems in the magnetosphere. It was also found that magnetopause reconnection was possible under both compressed and expanded magnetospheric conditions [Jasinski et al. 2016; Arridge et al. 2016a], and that the reconnection process could proceed in an unsteady fashion and at various locations on the magnetopause [Jasinski et al. 2014, 2016; Arridge et al. 2016a]. Cavities, where the plasma reduced the local magnetic field strength, were also detected, similar to Earth and Mercury, but at Saturn, the plasma was less capable of reducing the magnetic field strength, and there were important morphological differences due to the presence of internal plasma in the magnetosphere [Jasinski et al. 2017]. Saturn's cusp is the most thoroughly surveyed amongst the giant planets, and sets important context for the Juno mission at Jupiter.

Disk-like magnetosphere

Saturn's magnetosphere is an example of a rapidly rotating system dominated over much of its extent by a large magnetodisk of rotating plasma, this material falling further behind corotation with the planet as we go to larger distances from the planet. Because the system is so large, centrifugal force becomes very effective at keeping the cold plasma confined as this near-equatorial disk. In order to develop a first-principles model of Saturn's magnetodisk region, Achilleos et al. [2010a] adapted a model of field and plasma developed for the Jovian system by Caudal [1986], using plasma data available at that time to constrain the model's boundary conditions. This model was successfully used to explain the observed response of the planet's magnetospheric field to changes in system size. We were also able to compare the model contributions to the total magnetodisk current associated with the various forces on the plasma—centrifugal force and pressure gradient force—for both the Kronian and Jovian magnetodisk systems. A follow-up study by Achilleos et al. [2010b] explored particularly the influence of global changes in the energetic particle population on Saturn's magnetodisk structure. This model was also used in a study by Sorba et al. [2017], who developed theoretical compressibility curves showing how the magnetodisk size responds to changes in solar wind pressure and internal plasma content (energetic particles). These theoretical results were in good agreement with the observational analysis of Pilkington et al. [2015b] and we were also able to use the model to explain why one would expect the compressibility of the system to vary with system size. We have also had some success in using this magnetodisk model, combined with the current sheet elevation model of Arridge et al. [2011a], in order to model global, near-planetary-period oscillations in the magnetic field and plasma properties [Achilleos et al. 2014].

It has been shown that periodic variations of the plasma density peak at different rotation phases depending on radial distance in the magnetosphere. We showed that this variation arises as a consequence of the interaction between simple rotation and the expansion and contraction of the magnetosphere associated with propagating compressional disturbances [Ramer et al. 2017]. Propagating compressional disturbances also cause the magnetopause to move in and out non-sinusoidally and somewhat asymmetrically [Kivelson and Jia 2014]. The simulation also explains



the dawn–dusk asymmetry of field configuration and plasma flows in Saturn’s magnetosphere [Jia and Kivelson 2016].

Drivers of magnetospheric dynamics

Saturn is often placed in between Earth (solar wind driven) and Jupiter (internally driven) in terms of its magnetospheric dynamics, but this is an oversimplified picture. Much work has been done to characterize the structure of the solar wind upstream of the planet. Jackman et al. [2004] analyzed several solar rotations worth of upstream IMF data while Cassini was approaching Saturn, and Jackman et al. [2005a] followed up with an analysis of the solar wind excursion on Cassini’s long first capture orbit. Overall, it was found that during the declining phase of the solar cycle, the IMF is structured into a very clear pattern of two compressions per solar rotation separated by rarefactions. This structuring is very useful because it helps to predict the phasing of intermittent driving of the magnetosphere by the solar wind. Jackman et al. [2004] developed an empirical formula to calculate how much open flux is generated through dayside reconnection, dependent on the IMF direction, the solar wind velocity, and assuming a certain length of a predicted reconnection x-line at the dayside magnetopause. This formula has since been widely used by many other authors, in particular to compare to auroral images that seem to indicate addition and removal of flux—for example, Badman et al. [2005, 2012]. The solar wind conditions at Saturn (and Jupiter) spanning all stages of the solar cycle were summarized in Jackman and Arridge [2011a]. Reconnection voltages were predicted to be slightly lower at solar minimum than solar maximum, while increased photoionization of the Enceladus torus at solar maximum can lead to a more plasma dominated system at this stage of the solar cycle.

In a review article [Khurana et al. 2018], we showed that both azimuthal and radial currents in Saturn’s magnetosphere exhibit local time asymmetries as has been reported in Jupiter’s magnetosphere. Further, in these magnetospheres, the corotation enforcement currents (CEC), which flow in the radial direction in the current sheet, rival the strengths of their azimuthal ring currents. We also reviewed our knowledge of the field-aligned currents (FACs) in these magnetospheres.

Before Cassini’s arrival, it was not clear what the role the solar wind played in driving the magnetosphere, and so understanding the coupling between the solar wind and the magnetosphere ... was an important goal.

Magnetic flux and plasma circulation

In Lai et al. [2016], we investigated the returning flux tubes in the inner Saturnian magnetosphere. By studying the location distribution of the flux tubes, we confirmed that their magnetic signatures are different depending on the background plasma environments. Inside the plasma disk, the returning magnetic field is enhanced in strength, while outside the plasma disk, the magnetic field is depressed in strength. We also suggested that the flux tubes break into smaller ones as they convect in. By statistically comparing the entrance and exit normal vectors of the flux tubes, we

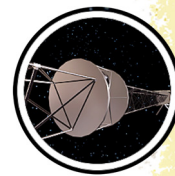


determined the shape of their cross-section. We found that it is closer to circular than fingerlike as produced in the simulations based on the interchange mechanism. In addition, no sudden changes in any flux tube properties can be found at the boundary, which has been claimed to separate the reconnection and interchange-dominant regions. By matching the magnetic flux transporting rate with the tail reconnection rate, a reasonable cold plasma loss rate (~ 150 kg/s) is derived. Meanwhile, the estimated outflow velocity agrees with earlier observations [Wilson et al. 2008].

Magnetotail structure

Cassini MAG measurements (often in concert with plasma measurements) have been used to characterize the tail in terms of distinguishing the lobe and plasma sheet regions and exploring how they change with distance from the planet. The current sheet is found to be warped out of the equatorial plane [Arridge et al. 2008a], with a characteristic hinging distance of $\sim 25 R_S$. This warping made a significant impact in Saturn's southern hemisphere summer in 2006 when Cassini executed its deepest tail orbits, first in the equatorial plane (below the hinged current sheet) and later at higher latitudes (close to the hinged current sheet). The current sheet has also been found to flap, or oscillate vertically with a period close to the ~ 10 hours linked to the mysterious planetary periodicities. Jackman and Arridge [2011b] performed a statistical study of Saturn's lobes and plasma sheet during 2006, developing numerical definitions for these regions, and deriving the falloff of the field strength in the lobes with radial distance. They found that the near magnetotail of Saturn is similar to that of Jupiter and Earth (when scaled to a common distance). Unlike at Earth, we do not have spacecraft coverage of the asymptotic tail region, but rather have likely only covered the part of the tail where the magnetopause boundary is still flaring outward and where the lobe field strength is falling off before reaching a steady asymptotic level. We do not know the exact length of Saturn's tail, but can consider arguments first made by Dungey [1965] for the Earth where length was estimated by time for open field lines to be dragged over the poles before ultimately sinking in toward the center of the tail before reconnection (giving $\sim 1,000 R_E$). Milan et al. [2005] examined the case at Saturn where the polar cap refresh time (i.e., the time for magnetic flux to be cycled through dayside to nightside reconnection) is expected to be many days—for example, Jackman et al. [2004] compared to a much shorter (~ 10 – 11 hours) planetary rotation period. This may be expected to twist the lobes of the tail and Milan argued each turn of a twisted lobe could be $\sim 900 R_S$ long. They theorized that Saturn is a last-in–first-out system in which recently opened field lines are the first to be closed by reconnection in the tail, due to this twist. This implies that Saturn's tail lobes contain a core of old open field lines that can be stretched to incredible lengths ($>15,000 R_S$).

It has been described how periodic compressional waves can account for periodic variation in the thickness of Saturn's nightside plasma sheet and proposed resonances as an explanation for the appearance of banded structure in ion dynamic spectra [Thomsen et al. 2017].



In situ observations of reconnection

Saturn's magnetosphere is observed to undergo dramatic, explosive energy release events. The first indication of such behavior was on the outbound pass of Saturn Orbit Insertion (SOI) where Bunce et al. [2005] reported an episode of solar wind compression-induced tail reconnection, with dipolarizing field and injection of hot plasma. The products of reconnection tailward of the x-line (plasmoids and travelling compression regions [TCRs]), were first observed with the Cassini magnetometer by Jackman et al. [2007]. They are identified primarily by a bipolar deflection in the north-south component of the field, with northward turnings implying reconnection products tailward of the x-line and southward turnings implying dipolarizations planetward of the x-line. Multi-instrument views of reconnection events reveal changes in the flow pattern from azimuthal to tailward and local heating of the plasma—for example, Jackman et al. [2008a]. It is sometimes observed that northward turnings are not purely bipolar but instead have an extended interval where the field remains northward. This has been interpreted as the Kronian equivalent of the post-plasmoid plasma sheet [Jackman et al. 2011], which represents an interval where previously open flux is being closed by reconnection.

Over the years, catalogs of reconnection events were built up from by-eye surveys and basic automation involving simple background thresholding of the magnetic field and searching for significant deflections above or below these thresholds. Surveys covering the deepest tail orbits of 2006 revealed a significant imbalance between the rate of mass loss inferred from plasmoid release and the rate of mass loading from the moon Enceladus, which has been termed the mass budget problem [Jackman et al. 2014]. More sophisticated automated event searches have returned surveys of >2,000 events from tail orbits during 2006, 2009, and 2010, and Smith et al. [2016] revealed that the rate of observed reconnection events peaked post-midnight, with a highly variable radial location of the reconnection x-line, with an average ranging from 20–30 R_S from the planet. To date only one study has identified the x-line region itself [Arridge et al. 2016b], while more recently Smith et al. [2018a] presented a series of very short duration reconnection-related inward and outward flows in quick succession on the dusk flank. Their interpretation was that over a 7-hour interval investigated, reconnection sites had formed both tailward and planetward of the spacecraft, showing that reconnection can operate on small spatial/temporal scales. A second case study showed an event during which the reconnection site was inferred to retreat tailward, resulting in progressively hotter, dipolarizing material reaching Cassini.

The properties of dipolarizations planetward of the x-line give us another view of the impact of reconnection on the magnetosphere. Jackman et al. [2013] published a case study that showed rapid acceleration of newly-reconnected field lines back toward the planet. The transition from a radially stretched to dipolar field configuration can cause a current which usually flows across the tail to divert into the ionosphere, potentially leading to bright, distinct spots of auroral emission. Jackman et al. [2015] further showed that dipolarization of the field can be accompanied by ion flows at speeds of up to 1,500 km/s toward the planet following tail reconnection, representing a significant departure from the slower, subcorotational flow typically seen in the tail. A reconnection event that starts at a small x-line can have a big impact on the magnetosphere as a whole.



Dipolarizations themselves have also been shown to have a dramatic effect on the local plasma: Smith et al. [2018b] investigated dipolarizations as identified from southward deflections of the magnetic field and found they were clustered preferentially post-midnight. The analysis of the accompanying CAPS data showed that the dipolarizing material was systematically hotter and less dense than the ambient plasma sheet. This density depletion and heating was found to be much more variable post-midnight, suggesting a more variable reconnection site.

Remote observations of global impact of reconnection

It is also important to consider how reconnection fits into the bigger picture of global magnetospheric dynamics. Jackman et al. [2016] reported that, like so many other phenomena, tail reconnection at Saturn is organized by northern and southern magnetic phase. Events are specifically linked to current sheet thinning and outward displacement of field and plasma. Little evidence was found for visibility effects associated with the north-south motion of the plasma sheet.

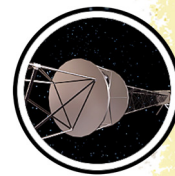
The question of whether reconnection is linked to internal or external drivers is an important one, and one approach to exploring this is to examine the radio data that accompany the magnetometer observations. Jackman et al. [2005b] explored concurrent IMF and SKR data from Cassini during Saturn Orbit Insertion. They showed that the SKR intensified and extended to lower frequencies coincident with the arrival of a solar wind compression, while many other studies have also explored this strong link between the radio power (and frequency) and the nature of the solar wind.

Jackman et al. [2009a] explored the SKR in more detail, focusing on several case studies where reconnection had been observed in Saturn's magnetotail. In general, they found a good correlation between the timing of reconnection events and enhancements in the SKR emissions. A physical mechanism was put forward whereby reconnection increases the precipitation of energetic particles into the auroral zones, leads to the formation of a potential drop, and thus stimulates the motion of the SKR source region to higher altitudes along the field line (and, hence, lower frequencies of radio emission). These low frequency extensions (LFEs) of the SKR were seen as strong proxies for dynamic solar wind compression and/or tail reconnection events.

Reed et al. [2018] attempted to automate the search for these LFEs in the SKR data and correlated 282 LFEs found during 2006 with a larger catalogue of reconnection events. LFEs were grouped into two categories, with short events of duration <20 hours separated by a median waiting time of ~10 hours, and strongly correlated with the northern and southern SKR phases. 60% of short LFEs have a reconnection event within the preceding 6 hours. The second category, long events, had duration >20 hours, often lasting multiple planetary rotations and associated with increases in solar wind dynamic pressure.

Saturn's magnetodisk current

Amongst the central goals of the Cassini magnetic field investigation is the characterization of the large-scale current systems that flow in Saturn's magnetosphere, their typical properties together



with their variability and dynamical behavior. The largest of these is Saturn's ring/magnetodisk current. This current flows in the equatorial magnetosphere eastward around the planet, extending the field lines radially outward and carried by the differential drift of ions and electrons in the plasma trapped on Saturn's magnetic field lines, which grades into the cross-tail plasma sheet current separating the lobes of the magnetic tail on the nightside. Although the existence of the ring current was first established from magnetic data acquired during the Pioneer-11 and Voyager flybys, little was known of the variability of the current, and its physical nature remained a matter of controversy, whether due to centrifugal action of the plasma mass or to the effect of plasma pressure. Data from the initial sequence of near-equatorial Cassini orbits was first used to determine the strength and radial extent of the current, showing that these vary strongly with the size of the magnetosphere dependent on the dynamic pressure of the impinging solar wind [Bunce et al. 2007]. While the inner edge of the current lies nearly unvaryingly at an equatorial radial distance of $\sim 7 R_s$, the radius of the outer edge varies between $\sim 15 R_s$ when the magnetosphere is strongly compressed to $\sim 22 R_s$ when it is significantly expanded, these distances typically lying only few R_s inside the dayside magnetopause. Correspondingly, the total eastward current varies from ~ 9 to ~ 15 MA, with a magnetic dipole moment that varies between ~ 0.2 and ~ 0.6 that of the internal field of the planet. A consequence is that while the dayside and comparably near nightside field is quasi-dipolar in form when the system is compressed, the field lines extend into an equatorial magnetodisk when it is expanded [Bunce et al. 2008a]. Later, when data from the first highly inclined Cassini orbits became available, the first direct measurements of the north-south thickness of the current sheet were also made, with values being typically $\sim 3 R_s$ on the dayside, while varying between ~ 1 and $\sim 5 R_s$ on the nightside [Kellett et al. 2009].

Cassini/MAG data revealed the magnetodisk [Arridge et al. 2008b; Bunce et al. 2008a] was particularly sensitive to the solar wind pressure, essentially disappearing on the dayside when the magnetosphere was compressed by the solar wind and explaining why it was not detected by Pioneer 11 or Voyager 1 and Voyager 2 [Arridge et al. 2008b].

The current sheet was also found to be warped out of the equatorial plane, as expected by analogy with Earth and Jupiter, but it was also found to be deformed at noon. Effectively the current sheet had the geometry of a shallow bowl, or upturned umbrella [Arridge et al. 2008a]. Subsequently, a detailed study of data from Earth's magnetosphere, inspired by Cassini/MAG measurements at Saturn, has revealed a similar effect at Earth [Tsyganenko and Andreeva 2014]. Superimposed upon this global warping was a flapping motion that occurred in phased with other periodicities in Saturn's magnetosphere [Arridge et al. 2008c, 2011b] and which had a lag or delay that propagated into the outer magnetosphere. However, latitudinal effects were also shown to play an important role, connected with differing periods in the northern and southern hemispheres [Provan et al. 2012].

Small ripples were also found superimposed on this bowl-shape [Arridge et al. 2007] that are largely propagating away from Saturn, indicating a source closer to the planet, possibly produced by plasma transport in the inner/middle magnetosphere [Martin and Arridge 2017].



The presence of the current sheet, and its deformation into a bowl shape, has important consequences for Titan's magnetic and plasma environment, and so the structure of its induced magnetosphere [Backes et al. 2005; Arridge et al. 2011b; Simon et al. 2013], as not only is the magnetic field (oriented in a different location to that found by Voyager 1) but also the bowl-shaped current sheet means that the Titan is not continuously immersed in Saturn's magnetospheric plasma.

Detailed collaborative work with the CAPS, MIMI, and Radio and Plasma Wave Science (RPWS) teams also examined the physical nature of the current [Kellett et al. 2010, 2011; Sergis et al. 2018]. It was shown that inside $\sim 10\text{--}12 R_s$ the current is carried principally by the relatively unvarying population of warm (~ 100 eV) water plasma picked up from the Enceladus torus, comprising principally of inertia and pressure anisotropy currents. Beyond these distances it is carried mainly by the more variable hot tenuous plasma (~ 10 keV and above) periodically injected from the tail, forming a pressure gradient current (see section entitled Saturn Storms). While, by analogy with Earth, the term ring current particles is often taken to be synonymous with hot injected plasma, this usage has thus proven to be inappropriate at Saturn, since the outwardly-transported warm water plasma is at least as significant in carrying the current.

In a publication dealing with periodic current sheet tilt [Khurana et al. 2009], we provided evidence that Saturn's inner/middle magnetosphere contains semi-permanent azimuthal anomalies in the magnetodisk current region in the fluxes of energetic charged particles, plasma density, magnetic field, and electrical current with a longitudinal wave number $m = 1$. We demonstrated that in the presence of these anomalies and a finite solar elevation angle, the solar wind lifts Saturn's magnetosphere asymmetrically in longitude, generating a tilt in the current sheet of Saturn.

Current sheet dynamics

Current sheets are also locations where dynamical behavior can be detected and studied. Magnetic reconnection is one important dynamical process that has been studied in detail with Cassini/MAG. Most studies only remotely or indirectly inferred that reconnection was happening—they were detecting the smoke from a distant fire. The location of the fire, the ion diffusion region, remained undetected until MAG played a critical role in the detection and analysis of an ion diffusion region in Saturn's magnetotail [Arridge et al. 2016a]—the only diffusion region to be detected and studied at a giant planet. This revealed the presence of fast magnetic reconnection and highlighted the possible effects of a multicomponent plasma, as studied in the terrestrial magnetosphere. The observations were used to examine the poorly understood mass and magnetic flux transport process, previously referred to as the mass crisis, where the observations of mass loss and magnetic flux transport were insufficient to balance transport and sources in other parts of the system. The observations showed that mass and flux could be conserved, and that undersampling may play a role in generating an apparent crisis. Using MAG, we were able to show that the geometry of the current sheet was important in the correct detection and interpretation of reconnection signatures [Jackman et al. 2009a]. Study of the current sheet has also revealed dynamical behavior connected with the ionosphere. Felici et al. [2016] presented evidence for



plasma flowing out of the ionosphere into the magnetotail where magnetic reconnection was also occurring. This revealed evidence for strong magnetosphere-ionosphere coupling associated with magnetic reconnection that drove outflow from the ionosphere into the magnetosphere.

Planetary period oscillations

Although the singular phenomenon of Saturn's PPOs was first observed by the Voyagers in modulated SKR emissions observed remotely from the planet, and later noted in both Voyager and Pioneer-11 magnetospheric magnetic data, Cassini observations have demonstrated the near ubiquity of oscillations near the planetary rotation period in essentially all magnetospheric plasma, field, and wave data despite the close axisymmetry of the internal planetary magnetic field. Initial work on the magnetic PPOs established their basic properties, first confirming the rotational nature of the oscillations via the Doppler effect of the azimuthal spacecraft motion [Cowley et al. 2006], and second showing that while the perturbation fields in the equatorial region are quasi-uniform in nature [Andrews et al. 2010a], rotating in the equatorial plane as indicated by the earlier flyby studies, the fields at high latitudes are instead quasi-dipolar in form [Provan et al. 2009a], associated with a rotating transverse dipole. The dipole moment is not internally generated by the planet, however, but by an external current system coupling the ionosphere and magnetosphere (see section entitled Field-Aligned Currents). The PPOs are thus associated with a second large-scale current system, and, due to their ubiquitous nature, have proved to be a major aspect of the Cassini Magnetic Field Investigation throughout the mission. In addition, their imprint is seen more widely in the entire Cassini magnetosphere data set. It was shown that the radial distance of the dayside magnetopause and bow shock are also significantly modulated by this phenomenon [Clarke et al. 2006, 2010a, 2010b].

With the further realization, initially from SKR data, that two such oscillations are generally present at the same time with slightly different periods, one associated with the northern polar region and the other with the southern, it was shown that the phase jitter in the equatorial magnetic oscillations previously observed is due to the vector superposition of the two systems [Provan et al. 2011], while the polar oscillations were found to be pure northern and southern on the central polar field lines in the two hemispheres [Andrews et al. 2012]. Cassini data from the deeper tail passes in 2006 correspondingly showed that while the two tail lobes are modulated at their separate polar periods, mixed signals are again present within the plasma sheet that are associated with both north-south oscillations of the current layer together with significant modulations in its thickness [Provan et al. 2012; Szego et al. 2013; Nemeth et al. 2015, 2016]. A model of these PPO-related variations has been derived, which provides a simple explanation of the sawtooth plasma sheet field variations observed during equinoctial conditions of near-equal northern and southern PPO amplitudes [Cowley et al. 2017; Thomsen et al. 2017]. The model has further been

The final proximal orbits have provided access to previously unexplored field lines crossing and inside Saturn's ring system.



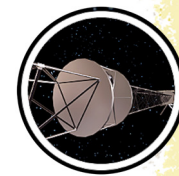
successfully applied to the more northern-dominated conditions prevailing during northern spring [Cowley and Provan 2017].

With the additional realization that the two PPO periods slowly change with Saturn's seasons by $\sim\pm 1\%$ about ~ 10.7 h (i.e., $\sim\pm 6$ min), a long-term program of precise ($\sim\pm 10$ s) measurement of the magnetic oscillation rotation period and phase has been carried out over the whole Cassini mission [Andrews et al. 2008, 2010b, 2012; Provan et al. 2013, 2014, 2016, 2018]. The results have subsequently been employed by many Cassini and Hubble Space Telescope (HST) teams as a framework to organize their data. The two PPO periods were found to be well-separated in late southern summer conditions at the beginning of the Cassini mission, ~ 10.6 h for the northern system and ~ 10.8 h for the dominant southern system, but then slowly converged with near-equal amplitudes to a near-common value ~ 10.7 h over a ~ 2 (Earth) year interval centered near vernal equinox (August 2009) [Andrews et al. 2012]. There followed a ~ 3 -year interval in early northern spring when the relative amplitudes changed abruptly at ~ 100 – 200 -day intervals between southern and northern dominance and near-equal amplitudes [Provan et al. 2013], the southern period ~ 10.69 h remaining slightly longer than the northern ~ 10.65 h, before the periods of the two systems coalesced at ~ 10.70 h in antiphase during the first half of 2014 [Provan et al. 2016]. In mid-2014, the period of the then-dominant northern system began to increase towards ~ 10.8 h, similar to the southern system in southern summer, while the southern period remained near-fixed at ~ 10.7 h, thus leading to the first enduring reversal in PPO periods, northern longer than southern, during the Cassini era. The periods remained close to these values across northern summer solstice in May 2017 to the end of mission [Provan et al. 2018]. Possible physical origins of the post-equinox interval of abrupt changes have been discussed in terms of both atmospheric effects [Cowley and Provan 2013] and solar wind influences during the rising phase of the solar cycle [Provan et al. 2015], though clear causality remains to be demonstrated. An additional important theme of these studies has been the comparison of the magnetic field phases and periods with those derived independently by others from analysis of SKR modulations. Although some areas of contention have been debated [Yates et al. 2015a, 2015b; Cowley and Provan 2015, 2016], the overall picture is one of good agreement [Andrews et al. 2008, 2010b, 2011, 2012; Provan et al. 2014, 2016].

The final proximal orbits have provided access to previously unexplored field lines crossing and inside Saturn's ring system. The behavior of the PPO oscillations on these field lines is presently under intense investigation.

Theoretical work [Southwood and Kivelson 2007] describes how a system of rotating field-aligned currents (cam currents) located on a magnetic shell in the range $L = 12$ – 15 would account for the periodicity observed in the magnetic field perturbations near the equator. Later, it was shown that the interaction of the rotating cam currents would interact with the global magnetic structure of the magnetosphere to produce periodic variations of current intensity and account for the modulation of the power of SKR [Southwood and Kivelson 2009].

A series of papers elucidated how appropriately placed vortical flows in a rotating ionosphere drive field-aligned currents consistent with the cam current previously proposed. These rotating



currents were shown to provide a quantitatively consistent description of all of the periodic dynamics reported in the system [Jia, X. et al. 2012a; Jia and Kivelson 2016; Kivelson and Jia 2014]. Theoretical work continues to best understand the origin of the two rotations rates [Southwood 2011, 2014, 2015; Southwood and Cowley 2014; Southwood and Chane 2016].

Field-aligned currents

A further major area of study for the Cassini Magnetic Field Investigation relates to large-scale field-aligned current systems, which couple the magnetosphere to the planet's upper atmosphere, ultimately producing the auroral displays seen in images, for example, at ultraviolet (UV) wavelengths. As in other magnetized environments, field-aligned currents in Saturn's magnetosphere play a fundamental role in the transfer of momentum along field lines between the ionosphere, the magnetosphere, and (potentially) the solar wind. At their ends, such currents close cross-field in association with $j \times B$ forces on the corresponding plasmas. Field-aligned currents further relate to the generation of bright discrete auroral forms at ionospheric heights, if current densities directed away from the planet exceed that which can be carried by the ambient precipitating magnetospheric electrons, at which point the latter are accelerated downward into the ionosphere by field-aligned voltages where they deposit their charge and energy. Initial theoretical expectations for Saturn related to meridional magnetosphere-ionosphere currents associated with the transfer of angular momentum from the planet's ionosphere to the net radially-outward transported equatorial plasma principally of Enceladus origin, i.e., the subcorotation currents [Cowley et al. 2004], together with dawn-dusk asymmetries associated with the solar wind interaction [Jackman and Cowley 2006].

Observationally, field-aligned currents are detected and quantified via variations in the azimuthal magnetic field on high-latitude and relatively low-altitude passes across the planet's polar regions. The first such data were acquired by Cassini/MAG in 2006/2007, with simultaneous HST UV imagery on one pass confirming that Saturn's auroral oval indeed maps into a region of upward current requiring downward acceleration of the observed magnetospheric electrons [Bunce et al. 2008b; Cowley et al. 2008]. An overall survey of these data showed that while their basic properties are consistent with theoretical expectations for subcorotation currents, with ~ 6 MA flowing down into the central polar ionosphere and the same return current flowing upward at lower latitudes in the auroral region, the currents are also modulated by the PPOs [Talboys et al. 2009a]. A much larger data set was then acquired in 2008 that allowed statistical studies to be undertaken [Talboys et al. 2009b, 2011]. It further allowed detailed exploration of the PPO dependence by comparing currents observed under conditions of differing PPO phase [Hunt et al. 2014, 2015, 2018a].

The principal PPO currents are found to be directed upward in a given hemisphere and downward on the opposite hemisphere of the planet's polar ionosphere, and rotate around the pole at the PPO period of the corresponding hemisphere. They are also approximately colocated with the upward current region of the subcorotation system, and of comparable strength, such that where the PPO current flows down, the total field-aligned current is reduced near to zero, while where it flows up the current is doubled, thus suggesting a dynamical connection. It is also found



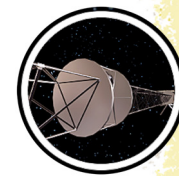
that the auroral region oscillates in latitude with amplitude $\sim 1^\circ$ in concert with these rotating modulations [Nichols et al. 2008; Provan et al. 2009b; Hunt et al. 2014; Bunce et al. 2014]. A complementary multi-instrument study also established the typical locations of the boundary of open field lines in the two hemispheres at $\sim 13^\circ$ colatitude in the north and $\sim 16^\circ$ in the south [Jinks et al. 2014], showing that the main PPO field-aligned currents flow just equatorward of this boundary on closed field lines. Correspondingly, interhemispheric coupling along closed magnetospheric field lines also occurs between the two PPO systems [Hunt et al. 2015; Provan et al. 2018]. Overall, the form of the PPO currents is consistent with driving by rotating twin-vortex flows in the two polar thermospheres/ionospheres [Hunt et al. 2014; Southwood and Cowley 2014].

Comparison between the 2008 data, obtained in the midnight sector, with the dawn-dayside data from 2006/2007 showed little difference, confounding expectations of observing long-term current asymmetries associated with the solar wind interaction [Hunt et al. 2016]. Highly unusual current distributions are observed in a small subset of passes, however, some of which have been associated with Saturn auroral storm solar wind compression events (see section entitled Saturn Storms) [Bunce et al. 2010]. Significant solar wind-related currents thus do flow in Saturn's magnetosphere at least intermittently. Indirect evidence of less dramatic solar wind effects have been obtained from HST studies of the dayside auroras (though not directly in field data), using Cassini as an upstream monitor of the IMF. Morphological auroral differences are found depending on the sense of the north-south component of the IMF, suggestive of dayside reconnection and related driving of flows and currents when the IMF points north [Meredith et al. 2014]. More generally, collaboration with colleagues at Moscow State University has resulted in the development of Saturn magnetospheric field models validated with Cassini data, which incorporate ring/tail and magnetopause currents, and are also parameterized by the strength and direction of the IMF [Alexeev et al. 2006; Belenkaya et al. 2006, 2007, 2010, 2011, 2014, 2016]. These models have been used during intervals when Cassini was located in the solar wind measuring the impinging IMF to map auroral features observed by the HST along field lines into their magnetospheric source regions, namely the middle and outer ring current region typically at dawn, and to the vicinity of the open-closed field boundary for high-latitude emissions near noon.

While the 2006/2007 and 2008 high-latitude data sets both correspond to Saturn's late southern summer, a third interval of high-latitude data was obtained in 2012/2013 during northern spring [Bradley et al. 2018]. The PPO currents were found to be of similar form but somewhat weaker than in 2008, while the subcorotation currents exhibited strong opposite seasonal asymmetries in the north and south polar regions, indicative of weak polar ionospheric conductivity in the winter polar cap. Investigation of the current signatures observed on the F-ring and proximal orbits spanning northern summer solstice at the end of the Cassini mission are currently ongoing [Hunt et al. 2018b].

Saturn auroral storms

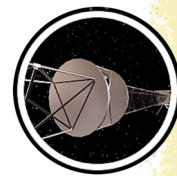
Although Voyager radio data had previously demonstrated that SKR emissions are strongly positively correlated with solar wind dynamic pressure, the nature of the related magnetospheric



dynamics remained unknown. This was partially revealed in early 2004 during the Cassini approach to Saturn when an intensive HST campaign imaging Saturn's UV auroras was undertaken, with Cassini acting as upstream solar wind/IMF monitor. As expected during the declining phase of the solar cycle, the recurrent solar wind structure consisted of two corotating interaction regions (CIRs) per ~ 25 -day solar rotation, exhibiting two few-day compression events of enhanced dynamic pressure, one major and one minor [Jackman et al. 2004]. The HST caught the impingement of the major compression region on Saturn's magnetosphere towards the end of the campaign, and observed a major increase in UV and SKR emissions with bright auroral forms extending throughout the dawn sector up to the planetary pole itself [Clarke et al. 2005; Bunce et al. 2006]. It was suggested that such auroral storms are caused by major bursts of compression-induced reconnection in Saturn's nightside tail, that inject hot plasma towards Saturn, which subsequently flows around the planet via dawn under the action of magnetosphere-ionosphere coupling [Cowley et al. 2005]. Estimates of the reconnection rate yielded associated voltages of at least several hundred kV [Badman et al. 2005]. Monitoring of the interplanetary field prior to SOI showed that the same compression region would likely impinge on the system during the SOI fly-through of the magnetosphere [Jackman et al. 2005a, 2005b], and indeed did, with a corresponding magnetic dipolarization event, plasma energization, and enhanced SKR emissions being observed in the nightside magnetosphere on the outbound pass [Bunce et al. 2005]. Analysis of a larger number of compression events observed by Cassini acting as upstream IMF monitor during the approach phase, as well as outbound after SOI in late 2004, also showed characteristic enhancements in SKR, but with the regular pulsing at the PPO period generally being undisturbed in phase [Badman et al. 2008].

Studies led elsewhere subsequently detected numerous reconnection-related events during the main Cassini tail exploration interval in 2006, namely planetward-travelling dipolarizations and tailward-travelling plasmoid structures, which were found to be related in timing to both the pulsing of the SKR emissions and the magnetic PPO phase [Jackman et al. 2009a, 2016]. Specifically, the events were found to be preferentially initiated during intervals when the PPO perturbations stretch the field lines radially outward from the planet and thin the plasma sheet leading to instability (see section entitled Planetary Period Oscillations), especially when the two PPO systems act in this manner in concert, i.e., when they are near antiphase. Ongoing work is presently investigating dipolarization events and auroral storms during the sequence of proximal orbits observed just prior to end of mission.

A further important related topic concerns the mass loss associated with plasmoid release down-tail as part of the Vasylunas cycle, compared with the $\sim 100 \text{ kg s}^{-1}$ Enceladus water plasma source rate. Although simple estimates based on the duration of observed plasmoid field perturbations yield mass loss values at least an order of magnitude smaller than this, given the typically several-hour interval between plasmoid releases, it has been suggested that the overall plasma structure released by such events may be at least an order of magnitude longer than the few tens of R_s lengths inferred from the magnetic data directly [Cowley et al. 2015].



Wave analysis

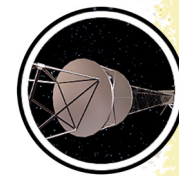
Preparatory studies concentrated on ultra-low frequency (ULF) waves in the Kronian magnetosphere and the resonant mode coupling process—for example, Cramm et al. [1998]. Later studies on plasma waves were conducted using observations made during the Cassini Earth flyby and after orbit insertion—for example, Bogdanov et al. [2003]; Kleindienst et al. [2009]. A more recent study of ULF waves has been carried out [Yates et al. 2016].

Saturn's Internal Magnetic Field and Implications for Interior Structure

Numerous planetary magnetic field models have been developed over the time of the Cassini orbital mission at Saturn beginning with Saturn Orbit Insertion [Dougherty et al. 2005]. Burton [2009] derived a model of Saturn's internal planetary magnetic field based on data obtained from the first three years of the mission, from July 1, 2004–July 1, 2007. Due to the uncertainty in the rotation rate, the model was constrained to be axisymmetric. In that analysis, one-minute averages of the vector magnetic field data obtained by the fluxgate magnetometer from all orbits within 10 R_S ($1 R_S = 60268$ km). Data from 45 orbits were used in that study. The contribution of the eastward flowing ring current is known to be significant close to the planet. Its contribution was modeled using the analytical expression derived by Giampieri and Dougherty [2004a] based on the simple axisymmetric equatorial current sheet centered on the planet's equator, first described by Connerney et al. [1981]. The ring current magnetic field was modeled separately for the inbound and outbound legs of each orbit because the current sheet structure and characteristics are known to vary with local time [Arridge et al. 2008b] and temporal variations in the solar wind and magnetosphere are likely to occur over time scales corresponding to that of a periapsis pass (several days). The ring current field was modeled and removed from the data and standard generalized inversion techniques were used to model the magnetic field presumed to originate in Saturn's interior.

The internal field model derived in that study was found to be quite consistent with previous models. An axisymmetric octupolar (degree 3) model was found to fit the data adequately based on an examination of the root-mean-square misfit or residual for each orbit. The spherical harmonic coefficients derived were $g_{10} = 21,162$, $g_{20} = 1514$, $g_{30} = 2283$. Units are nanoteslas (nT) and are based on a planetary radius of 60,268 km. Saturn's magnetic was found to be offset northward by 0.036 Saturn radii, consistent with earlier Pioneer-11 and Voyager models. Reanalysis and comparison with data obtained by Pioneer 11 and Voyager 1 and 2 showed little evidence for secular variation in the field in the almost 30 years since those data were obtained.

A subsequent study [Burton 2010] used data from the entire Cassini Prime Mission (through July 2008) and a methodology that differed in significant ways from the earlier modeling approach [Burton 2009]. Only data obtained at radial distances closer than the L-shell of Enceladus (dipole L-value of 3.8) were used to derive the model. Measurements obtained by all Cassini fields and particles instruments had demonstrated that the structure and dynamics of Saturn's inner magnetosphere are governed by plasma created at Enceladus [Kivelson 2006]. The observed field



at radial distances outside the orbit of Enceladus is modified by processes in the inner magnetosphere and does not necessarily reflect the magnetic field generated in Saturn's interior.

The approach to modeling the external ring current field also differed from the earlier modeling approach. As time went on, our understanding of Saturn's magnetodisc had evolved and a simple symmetric ring current centered on the equator was no longer thought to be an accurate representation. Instead, the current sheet was found to be displaced from Saturn's rotational equator and to assume the shape of a bowl or basin, referred to as a magnetodisc [Arridge et al. 2008b]. Instead of modeling the external field as an oversimplified axisymmetric ring current as in Burton [2009], the internal plus external field was modeled using the standard spherical harmonic formulation and a single set of spherical harmonic coefficients was obtained that describes the internal and external field in a least squares sense. Accordingly, the axisymmetric model coefficients differ somewhat from the previous model.

In Burton [2010], an attempt was made to determine the planetary rotation rate by deriving a number of non-axisymmetric magnetic field models for a plausible range of planetary rotation periods and assessing the power in the non-axisymmetric components of the field and the root-mean-square misfit between the model and the data. The methodology is as follows. A presumed planetary rotation period was varied in one-second increments from 10 hours 28 minutes to 10 hours 40 minutes and a pseudo-longitude calculated for each measured data point. A degree 3, non-axisymmetric magnetic field model was derived and the power in the non-axial magnetic field and the misfit were calculated. The underlying premise is that the planetary rotation period could be determined based on a peak in the non-axial power and minimum in the misfit. Although no such peak was identified unambiguously, the analysis did provide an upper limit on the extent of the dipole tilt. Based on the distribution of the non-axial spherical harmonic model coefficients for the range of rotation rates, a mean value for the dipole tilt was determined to be 0.03 degree. The upper limit of all tilt angles was found to be 0.1 degree.

We have further developed the state-of-the-art internal magnetic field model for Saturn using Cassini magnetometer measurements prior to the Grand Finale, which placed the most stringent constraint to date on the tilt and secular variation of Saturn's intrinsic magnetic field [Cao et al. 2011]. The tilt of Saturn's dipole must be smaller than 0.06 degree from the spin-axis of Saturn, and the time variation of Saturn's intrinsic magnetic field must be an order of magnitude slower than that of the Earth's [Cao et al. 2011]. These results are very challenging for dynamo theory, as Cowling's theorem excludes the possibility of a purely axisymmetric magnetic field being maintained by dynamo action.

We have also derived degree 4 and degree 5 internal magnetic moments for Saturn, albeit with relatively large uncertainties, from reanalyzing the Cassini SOI MAG measurements [Cao et al. 2012]. Based on these observational findings, we worked out the implications on helium rain inside Saturn [Cao et al. 2011, 2012]. These also provided the framework for our current analysis of the magnetometer measurements from the Cassini Grand Finale.



The latest Cassini Grand Finale gravity measurements indicate that the ~ 100 m/s zonal flows observed at the cloud deck of Saturn extend almost 10,000 kilometers into the planetary interior. Given that the electrical conductivity at such depth are high enough for significant MHD effects, zonal flow magnetic field interaction in the semi-conducting region of Saturn is now a central issue in understanding the interior dynamics. On the theoretical side, we have developed a mean-field model for zonal flow magnetic field interaction in the semi-conducting region of Saturn [Cao and Stevenson 2017]. In this work, we proposed that the interaction between zonal flow and a magnetic field in the semi-conduction region of Saturn would generate small-scale axisymmetric magnetic fields that are spatially correlated with zonal flows [Cao and Stevenson 2017]. The amplitude of the wind-induced magnetic perturbations would depend on the amplitude of the deep differential rotation as well as the amplitude of the small-scale deep convective flow. Thus, measuring/constraining wind-induced magnetic perturbations along the Cassini Grand Finale orbits would place important constraints on the properties (profile and amplitude) of deep differential rotation and convective flow in the semi-conducting region of Saturn.

With magnetic field measurements at unprecedented proximity to Saturn by the Cassini Grand Finale [Dougherty et al. 2018], we are working on deriving: 1) non-axisymmetric internal magnetic moments of Saturn from the Cassini Grand Finale magnetometer measurements, which can tell us about the deep interior rotation rate of Saturn and/or helium rainout and stable stratification inside Saturn; 2) small-scale axisymmetric magnetic features—for example, high-degree axisymmetric internal magnetic moments—which can be used to constrain deep differential rotation inside Saturn; and 3) time variations in the internal magnetic fields, which would reveal characteristic time scale in Saturn's internal magnetic field and deep interior dynamics. These expected results would constitute the observational facts about the internal magnetic fields of Saturn for many years to come, which would further serve as tests for theories about giant planet interiors and have profound implications about giant planets outside the solar system.

Titan Science

The MAG team has significantly contributed to the understanding of the interaction between Saturn's major moon, Titan, and its plasma environment. The virtual absence of an intrinsic field at Titan makes this interaction mainly atmospheric as fields and charged particles from Saturn or the Sun impinge on the moon's chemically complex atmosphere, exosphere, and ionosphere. Atmospheric interactions are common elsewhere in the solar system with Mars and Venus as their most typical examples. In these cases, as well as in Titan's, charged particles from its atmosphere (originating from photoionization, charge exchange, and electron impact) become electromagnetically coupled to those carried by the plasma winds that flow past it [Bertucci et al. 2011].

The exchange of momentum and energy between the atmospheric charged particles and those being part of the external wind lead to a steady perturbation in the ambient external magnetic field known as induced magnetosphere and characterized by the draping of the external magnetic field lines around the unmagnetized, atmospheric body. Cassini MAG observations were crucial in



providing constraints to the structure of Titan's magnetotail [Bertucci et al. 2007b] and characterizing Saturn's magnetic field at Titan's location [Bertucci et al. 2009].

However, one of the most remarkable features revealed by MAG was that Titan's induced magnetosphere is formed by layers of different polarity of the external magnetic field that allows for reconstruction of the history of the moon's magnetic environment. Indeed, in the same way as older sediments lay beneath more recent deposits in geology, the magnetic fields fossilized in the deep layers of Titan's induced magnetosphere provide information about the orientation of the external field Titan was exposed up to three hours before the encounter with Cassini [Bertucci et al. 2008]. This magnetic memory of Titan is significantly longer than those at Venus and Mars and is a result of the capacity of Titan plasma to remove momentum from the external plasma. Cassini MAG data were also essential to characterize Titan's unique example of interaction with the supersonic solar wind [Bertucci et al. 2015] as structures found at Mars and Venus (an induced magnetospheric boundary and a collisional bow shock) were successfully captured by the instrument.

The Cassini Titan mission consisted of the encounters TA, TB, TC, T3, T4 ... T126 in project nomenclature, all with useful magnetic field data. The magnetic field conditions upstream of these flybys were strongly variable and different from the single encounter during the Voyager 1 mission—for example, Neubauer et al. [1984]. For example, the simple model derived from Voyager 1 with the flow along the direction of orbital motion and the magnetic field perpendicular to Titan's orbital plane was at most approximately fulfilled in rare cases.

The first part of the exploration strategy was to analyze individual encounters with particularly noteworthy characteristics. The first encounter TA on October 26, 2004, was carefully investigated and compared with the results of a newly developed numerical model. The comparison showed best agreement with a MHD-model, which separately described ionospheric (cold) electrons and magnetospheric (hot) electrons [Backes et al. 2005]. In joint studies of the TA flyby a comparison between MAG and RPWS-data was done by Wahlund et al. [2005] and a comparison between Cassini and Voyager data using both plasma spectrometer (PLS) and magnetic field data by Hartle et al. [2006]. The next more detailed study was using magnetic field and PLS electron data and included TA, TB, and T3 [Neubauer et al. 2006]. The data showed a draping boundary as the outer boundary of strong magnetic field draping. Further, the induced magnetospheric tail near Titan was investigated. The shape of the tail was found to be similar to a delta wing in aerodynamics. It was shown that the long travel time of frozen-in magnetic field lines into the lower ionosphere of Titan led to the observation of old or fossil field lines compared with their times of arrival in front of Titan. This concept was later called memory effect by Bertucci et al. [2008] in a paper discussing Titan encounter T32 which occurred for the first time in the Saturnian magnetosheath, but also contained old Saturnian magnetospheric field as a memory effect—see also Ma et al. [2009].

Titan's orbit is typically located inside Saturn's magnetosphere, but could occasionally move outside it into the magnetosheath or even into the solar wind.



The first opportunity to study the induced tail at medium distances occurred at T9, which led to a data analysis paper by Bertucci et al. [2007b]. It also led to a number of modelling papers that helped to disentangle the detailed plasma and magnetic field characteristics [Kallio et al. 2007; Wei et al. 2007; Ma et al. 2007] of the complex magnetotail.

These early Cassini/MAG data at Titan also led to the conclusion that an internal magnetic field of Titan was at most very small. Using the magnetic field observations on flyby orbits very close to Titan. Wei et al. [2010a] found an upper limit on the dipole moment of $0.78 \text{ nT} \times R_T^3$ improving the Voyager 1 upper limit by a factor of five.

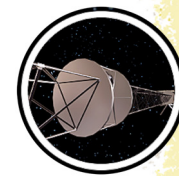
Considering further the ionosphere of Titan with its embedded magnetic field, a study of Titan's nightside ionosphere was published by Cravens et al. [2009]. Data collected along T96, the first encounter presumably occurring in the supersonic solar wind, was also compared to modeling results from a hybrid kinetic code [Feyerabend et al. 2016].

An important kinetic process in the interaction between a streaming magnetized plasma and Titan's atmosphere is the pick-up process, which has been observed to lead to the generation of often strong ion cyclotron waves in the cases of atmospheric interactions (Venus, Mars, Galilean satellites of Jupiter, Saturnian satellites, comets). In the case of Titan, only two flybys T63 and T98 were associated with ion cyclotron waves of relatively high amplitude, as a study of the MAG team shows [Russell et al. 2016].

In parallel to the studies of single flybys, we have also undertaken a systematic study of all Titan flybys by looking at the characteristics of the magnetic field variations upstream and also downstream of the interaction region proper close to Titan with duration $\pm 1 \text{ h}$. Most of the regions of $\pm 8 \text{ h}$ around the interaction region can be characterized as a sequence of intervals with magnetic fields of the northern/southern magnetospheric lobe type and the magnetospheric current sheet [Arridge et al. 2008c], which can be found near the magnetic equator. Mixtures of these regions do also occur. In rare cases, encounters occurred in the magnetosheath of Saturn (T32, T42, and T85) and in the solar wind (T96).

The individual results have been collected in Simon et al. [2010a, b] for TA–T62, Simon et al. [2013] for TA–T85 and Kabanovic et al. [2017] for the remainder. The latter paper also indicates appreciable variations of the occurrence of the types of magnetic field regions as a function of Saturnian season. Results are given for 2004–2008, 2009–2010, 2011–2017 for about half a Saturn year.

A special study of the magnetotails of Titan has investigated the tails by wake flybys with closest approach (CA) distances $> 2.5 R_T$ in the whole set of flybys TA–T84 [Simon et al. 2014a]. The resulting eight flybys confirmed the delta wing structure found in Neubauer et al. [2006] leading to a thickness of the wing of $\pm 3 R_T$. Magnetotail studies in the set T85–T126 have not been done yet.



Titan's orbit is typically located inside Saturn's magnetosphere, but could occasionally move outside it into the magnetosheath or even into the solar wind. To better understand the magnetic and plasma environment of Titan, the plasma environment at Titan's orbit is compared with Titan present and absent from 06/2004 to 12/2008. Cassini observations reveal that the presence of Titan appears to affect the magnetopause location. Near noon, the Saturn magnetopause is more frequently inside of Titan's orbit with the moon absent than with it present. Titan's presence near noon appears to locally enhance the total pressure and reduce the magnetosphere compressibility, possibly by mass-loading. Near local midnight, the stretching and sweepback angles for cases with Titan present and absent suggest that the moon enhances the tail reconnection rate, in agreement with previous studies of the moon's influence on the Saturnian magnetosphere [Wei et al. 2009].

Due to Titan's thick atmosphere, ion cyclotron waves are expected to be created when the atmospheric particles are ionized and picked up by Saturn's magnetospheric plasma. However, ion cyclotron waves are rarely observed near Titan, due to the long growth times of waves associated with the major ion species from Titan's ionosphere, such as CH_4^+ and N_2^+ [Cowee et al. 2010]. In the more than 100 Titan flybys obtained by Cassini, there are only two wave events, for just a few minutes during T63 flyby and for tens of minutes during T98 flyby. These waves occur near the gyrofrequencies of proton and singly ionized molecular hydrogen. From hybrid simulations for T63, we find the pickup protons with densities ranging from 0.01/cc to 0.02/cc and singly ionized molecular hydrogens with densities ranging from 0.015/cc to 0.25/cc can drive ion cyclotron waves with amplitudes of ~ 0.02 nT and of ~ 0.04 nT within appropriate growth times at Titan, respectively [Russell et al. 2016].

During the interaction between Titan's ionosphere and its ambient plasma, Cassini observations find that the lower ionosphere of Titan is often magnetized, with large-scale magnetic fields and some structures resemble magnetic flux ropes. These flux ropes are either starting to form or maturely formed, with their axial orientations in agreement with the theoretical formation mechanism [Wei et al. 2010b]. A special example of ionospheric flux rope is observed during Titan flyby T42. The observed magnetic field attained a maximum value of 37 nT between an altitude of 1,200 and 1,600 km, much larger than other similar passes. Cassini observations from the plasma and magnetic instruments indicate that Titan's ionosphere was strongly magnetized during an enhanced solar wind dynamic pressure interval right before this flyby, and it caused this large fossil field that later got further twisted while sinking into lower ionosphere [Wei et al. 2011].

The interaction between Titan and the corotating Saturnian plasma forms an induced magnetosphere with an elongated Alfvén-wing-style magnetotail. During the first mid-tail flyby T9, Cassini plasma and magnetic field instruments detected in one tail lobe a magnetic flux tube connected with ionosphere and filled with cold ionospheric plasma. This magnetic structure indicates that Titan's ionosphere appears to be escaping along field lines down the tail, leading to particle loss from the atmosphere [Wei et al. 2007].

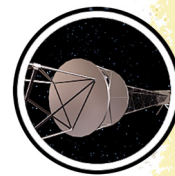
To understand the internal magnetic moments of Titan, the radial component of Cassini magnetometer observations near Titan surface (from 950 km to 1,100 km) was used to calculate the permanent dipole moment. The upper limit to Titan's permanent dipole moment is



$0.78 \text{ nT} \times R_{\text{Ti}}^3$, using the observations during the southern summer season of Saturn (April 2005 to March 2009). This weak internal field indicates the interior of Titan may not contain a liquid core sufficiently electrically conductive for a magnetic dynamo to be generated inside Titan or even for the simple amplification of the external magnetic field [Wei et al. 2010a]. For the signs of the calculated internal field components, the g11 and h11 component, corresponding with the Titan-to-Saturn direction and the corotation direction, respectively, are in agreement with the signs of the averaged ambient field around Titan during the observation period. This indicates that these estimated internal moments may be due to the penetration of the ambient field into the interior of Titan, generating induced fields. After Saturn's equinox, August 2009, the ambient field of Titan changes sign in the Titan-to-Saturn direction and the corotation direction, as Titan moved from below Saturn's current sheet to above it. Thus, we compared the calculated internal moments using the observations before and after Saturn's equinox, and found that the g11 and h11 moment changed sign in agreement with the sign of Titan's ambient field.

A multispecies MHD model has been employed to study plasma interaction with Titan, model results have been compared with several Cassini Titan flybys to better understand the plasma environment of Titan.

1. Ta and Tb flyby [Ma et al. 2006]: The Cassini spacecraft passed by Titan on October 26, 2004 (Ta flyby), and December 13, 2004 (Tb flyby). In both cases, the Cassini spacecraft entered Titan's ionosphere and flew through Titan's dynamic wake region. We simulated both flybys using our three-dimensional multispecies MHD model. The calculations used the best available upstream plasma and magnetic field parameters obtained by Cassini. Model results were compared with relevant plasma measurements and showed close agreement between the two, demonstrating that the general interaction features can be pretty well reproduced by the MHD model.
2. T9 flyby [Ma et al. 2007]: The wake region of Titan is an important component of Titan's interaction with its surrounding plasma. The Cassini spacecraft passed through the distant downstream region of Titan on December 26, 2005 (T9 flyby). In this study, we compared the observational data with numerical results using a three-species Hall MHD Titan model. There is a good agreement between the observed and modeled parameters, given the uncertainties in plasma measurements and the approximations inherent in the Hall MHD model. Our simulation results also show that Hall MHD model results fit the observations better than the non-Hall MHD model for the flyby, consistent with the importance of kinetic effects in the Titan interaction. Based on the model results, we also identified the controlling physical processes in different plasma regions based on ion gyroradius.
3. T32 flyby [Ma et al. 2009]: When the Cassini spacecraft flew by Titan on June 13, 2007, at 13.6 hr Saturn local time, Titan was directly observed to be outside Saturn's magnetopause. Cassini observations showed dramatic changes of magnetic field orientation as well as other plasma flow parameters during the inbound and outbound segments. We studied Titan's ionospheric responses to such a sudden change in the



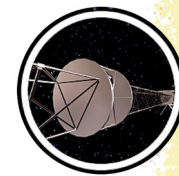
upstream plasma conditions using our multispecies global MHD model. Simulation results are compared against Cassini MAG, Langmuir Probe, and CAPS observations. The main interaction features, as observed by the Cassini spacecraft, are well reproduced by the time-dependent simulation cases. The simulation results provide clear evidence for the existence of a fossil field that was induced in the ionosphere due to a different convection time around Titan. These simulations also reveal how the fossil field was trapped during the interaction and shows the coexistence of two pileup regions with opposite magnetic orientation, as well as the formation of a pair of new Alfvén wings and tail disconnection during the magnetopause crossing process.

4. T34 flyby [Ma et al. 2011]: We improved the previously used multispecies MHD model by solving both the electron and ion pressure equations instead of a single plasma pressure equation. This improvement enabled a more accurate evaluation of ion and electron temperatures inside Titan's ionosphere. The model is first applied to an idealized case, and the results are compared in detail with those of the single-pressure MHD model to illustrate the effects of the model improvement. These simulation results show that the dayside ionosphere thermal pressure is larger than the upstream pressure during normal conditions, when Titan is located in the dusk region; thus Saturn's magnetic field is shielded by the highly conducting ionosphere, similar to the interaction of Venus during solar maximum conditions. This model is also applied to a special flyby of Titan, the T34 flyby, which occurred near the dusk region. It is shown that better agreement with the MAG data can be achieved using the improved MHD model with the inclusion of the effects of super thermal electron heating. This clearly demonstrates the importance of super thermal-electron heating in Titan's ionosphere.

Enceladus Science

The most significant highlight of the MAG investigation during the Cassini mission was the discovery of an atmospheric plume at Enceladus by the MAG team [Dougherty et al. 2006] on February 17, 2005, and confirmed and strengthened by subsequent measurements on later flybys and other instruments. The discovery of a thin neutral atmosphere by the magnetic signature of an electrodynamic interaction proved to point to one of the unique capabilities of the MAG experiment. In another MAG publication on Enceladus [Khurana et al. 2007], we showed that the effective diameter of the obstacle (the plume) is at least $6 R_E$, and the obstacle is displaced by $>2 R_E$ south of Enceladus and downstream by at least $1 R_E$. The total current produced in the interaction is $<10^5$ Amps (40–60% of the Neubauer limit). We estimated that the mass picked up by the plasma within $5 R_E$ of Enceladus is <3 kg/s.

This dynamic atmospheric plume was later shown by the Imaging team to be due to geyser activity on the southern hemisphere of Enceladus. The electrodynamic interaction involves southern and northern Alfvén wings such that the atmospheric influence not only shows up in the



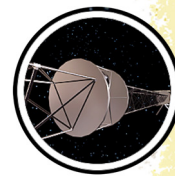
southern but also the northern wing—hemispheric coupling [Saur et al. 2007]. Using these concepts and magnetic field observations of flybys E0, E1, E2 and neutral density measurements at E2 the time variability of the plumes was investigated [Saur et al. 2008]. Subsequent modelling based on analytical theory clearly showed that the MAG results required the presence of negatively charged dust particles [Simon et al. 2011a]. The paper also proves the presence of the hemispheric coupling currents required by Saur et al. [2007]. The interaction was later modelled numerically in detail using a hybrid (fluid electron) kinetic code including charged dust particles [Kriegel et al. 2011]. As a unique feature at Enceladus, dust–plasma interactions play an important role to explain the observations.

Since Saturn has a rotation dominant magnetosphere powered by the plasma sources in its inner magnetosphere, quantifying the gas and plasma torus is crucial to understand the magnetospheric dynamics of Saturn. The primary source of the Saturnian torus is ejections from Enceladus. This newly released gas, dust, and plasma interacts with Saturn’s magnetosphere, and strong disturbances in the magnetic field are generated. We studied the magnetic signals observed by Cassini/MAG at Enceladus, to determine the gas and dust production rate at Enceladus and how do they vary with time.

The neutrals sent to space from Enceladus are partly ionized via photoionization, electron or proton impact ionization, and charge exchange processes. These new ions are loaded into the magnetosphere, which is, in turn, slowed down into an 80% subcorotation.

We employed a 3-D MHD model to simulate the plasma interaction at Enceladus. The model is applied to the Block Adaptive Tree Solar-wind Roe Upwind Scheme (BATS-R-US) code in an 80 x 80 x 160 Enceladus radii computational domain. The neutrals are treated as a background condition, with a density described by analytical functions: the torus component and a moon component that falls off by a factor of r^{-2} with distance. The upstream boundary is an inflow boundary, with density, velocity, temperature and field conditions obtained from the Cassini flyby data. The inner boundary at the Enceladus surface is absorbing the moon condition, which absorbs the inflow plasma, and fixes the outflow density as a floor value. The field has no gradient at the inner boundary. This code has been applied to a spherical obstacle in a plasma flow to show the effect of the moon and local pickup separately [Jia, Y. -D. et al. 2010a]. With this model, we have refined the plume geometry with E2 data [Jia, Y. -D. et al. 2010b] and constrained the outgassing rate of the Enceladus plume with data from the nine early flybys [Jia, Y. -D. et al. 2010c, 2010d].

Plume brightness is found to be varying by a factor of a few around the apocenter of Enceladus orbit, using visual images. In contrast, outgassing rate deduced from our data-modeling comparison suggested 50% variation in gas production rate during the first nine passes E0-E8 [Jia, Y. -D. et al. 2010c, 2010d]. The magnetometer could not confirm this postulation with local interaction data. Then, the field perturbation perpendicular to both the direction of magnetospheric flow, and to the magnetic field has been studied with our multi-fluid code, to illustrate the effect of charged dust in creating such a field perturbation [Jia, Y. et al. 2011].

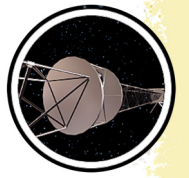


Other Icy Satellite Science

In addition to the large number of flybys at Titan and Enceladus, there was also a small number of targeted flybys of some of the other icy satellites. The magnetic signatures observed were used to investigate in detail the magneto-plasma interaction with these satellites with the help of 3-D hybrid kinetic models introduced before. On September 24, 2005, the only Tethys encounter took place close enough to the satellite to be diagnostically useful. No evidence for an atmosphere/ionosphere system was found. Instead, the magnetic field signatures were explained by the plasma absorption by the satellite [Simon et al. 2009a]. The Dione encounters on October 11, 2005 and April 7, 2010, led to the observation of Alfvén wing signatures. The analysis yielded an atmospheric column density of 10^{17} m^{-2} [Simon et al. 2011b]. The two flybys at Rhea on March 2, 2010, and January 11, 2011, were not associated with magnetic signatures due to the atmosphere, which was identified by other means. The magnetic signature was also dominated by plasma absorption features [Simon et al. 2012].

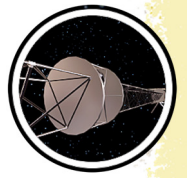
We characterized the submagnetosonic plasma interaction of Rhea in Khurana et al. [2008]. Main conclusions were: 1) Rhea is also an inert moon and devoid of any internal magnetic field; 2) no induction field was observed from any subsurface conductor; 3) no appreciable mass-loading occurs near Rhea; and 4) the region of plasma depletion is greatly elongated along the field direction. The submagnetosonic interaction of Rhea with the Saturnian plasma was further explored in Khurana et al. [2017] where we showed that the wake refilling process generates Alfvén wings in the wake region from a plasma density gradient force directed in the direction of corotating plasma. The plasma pressure gradient force slows down the plasma streaming into the wake along field lines. As on the same field lines, outside of the wake, the plasma continues to move close to its full speed; this differential motion of plasma bends the magnetic flux tubes, generating Alfvén wings in the wake. The current system excited by the Alfvén wings transfers momentum from plasma outside the wake to the wake plasma. Our work demonstrates that Alfvén wings can be excited even when a moon does not possess a conducting exosphere. In another work on Rhea's interaction with the Saturnian plasma [Teolis et al. 2014], we showed that sharp magnetic perturbations are present at the edge of the Rhea flux tube, which are consistent with field-aligned flux tube currents. We showed that the current system results from the difference of ion and electron gyroradii and the requirement to balance currents on the sharp Rhea surface.

On September 26, 2005, Cassini conducted its only close targeted flyby of Saturn's small, irregularly shaped moon Hyperion. Approximately 6 minutes before the closest approach, the electron spectrometer (ELS), part of the CAPS instrument detected a field-aligned electron population originating from the direction of the moon's surface. We showed that this constituted a remote detection of a strongly negative ($\sim 200 \text{ V}$) surface potential on Hyperion, consistent with the predicted surface potential in regions near the solar terminator [Nordheim et al. 2014].



MAG NON-SATURN SCIENCE RESULTS

Early science used the measurements along the flyby of Earth and Jupiter. The Earth flyby produced fairly original observations at high resolution of what appeared to be interchange motions on the nightside outbound pass. Inbound, high-resolution measurements of the whistler waves in the electron foreshock were reported. In addition, the down-tail passage allowed observation of two geomagnetic sequential substorm cycles [Southwood et al. 2001; Smith et al. 2001; Khan et al. 2001; Tsurutani et al. 2001]. Passage by Jupiter allowed coordination with Galileo during its 28th and 29th orbits. The most important conclusion was good evidence of changed magnetospheric shape in response to local solar wind magnetic field changes in the north-south component. There is increased flaring when the field is northward, opposite of what happens at Earth. As the Jovian dipole is oppositely oriented, this is consistent with reconnection being important to magnetospheric configuration at Jupiter despite the rapid planetary rotation [Kivelson and Southwood 2003, 2005].



ACRONYMS

Note: For a complete list of Acronyms, refer to Cassini Acronyms – Attachment A.

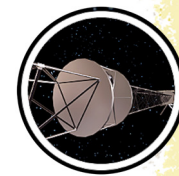
AO	Announcement of Opportunity
AU	astronomical unit
BATS-R-US	Block Adaptive Tree Solar-wind Roe Upwind Scheme
CA	closest approach
CAPS	Cassini Plasma Spectrometer
CEC	corotation enforcement currents
CIR	corotating interaction region
CSM	Cassini Solstice Mission
ELS	electron spectrometer
FAC	field-aligned current
FGM	Flux Gate Magnetometer
HST	Hubble Space Telescope
IMF	interplanetary magnetic field
LFE	low frequency extension
MAG	Magnetometer
MAPS	Magnetospheres and Plasma Science
MHD	magneto-hydrodynamic
MIMI	Magnetospheric Imaging Instrument
PLS	plasma spectrometer
PPO	planetary period oscillation
RPWS	Radio and Plasma Wave Science
SKR	Saturn kilometric radiation
SLT	Saturn local time
SOI	Saturn orbit insertion
TCR	travelling compression region
ULF	ultra-low frequency
UV	ultraviolet
V/SHM	Vector/Scalar Helium Magnetometer



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***Disclaimer:** The partial list of references below correspond with in-text references indicated in this report. For all other Cassini references, refer to Attachment B – References & Bibliographies; Attachment C – Cassini Science Bibliographies; the sections entitled References contributed by individual Cassini instrument and discipline teams located in Volume 1 Sections 3.1 and 3.2 Science Results; and other resources outside of the Cassini Final Mission Report.*

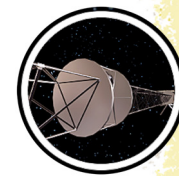
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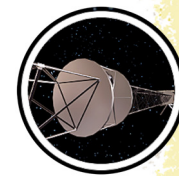
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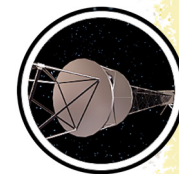
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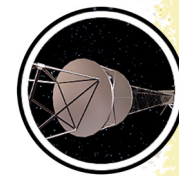
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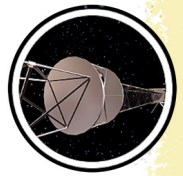
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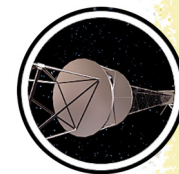
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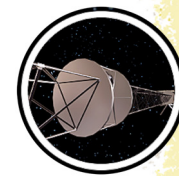
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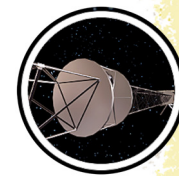
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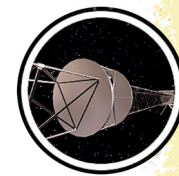
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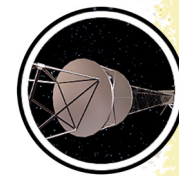
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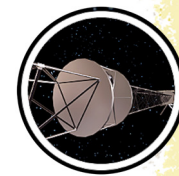
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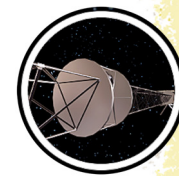
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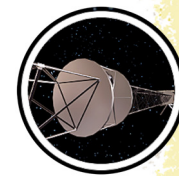
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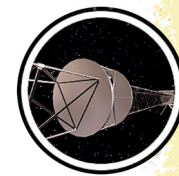
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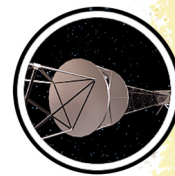
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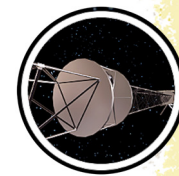
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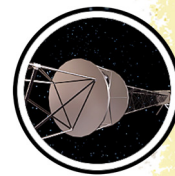
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