MAPPING MAGNETOSPHERIC REGIONS AT SATURN: A MINI JOVIAN ANALOGUE?

C.S. Arridge, H.J. McAndrews, N. André, E.J. Bunce, K.C. Hansen, R.E. Johnson, G.H. Jones, S. Kempf, K.K. Khurana, N. Krupp, W.S. Kurth, C. Paranicas, C.T. Russell, E.C. Sittler, and M.F. Thomsen

Proposal in response to the announcement of Research Opportunities for International Teams: International Space Science Institute

Abstract

In July 2004 the Cassini spacecraft entered Saturn orbit after a seven year voyage. The combined operation of an outstanding suite of instruments with the orbital tour of the spacecraft offers a unique opportunity to explore in-depth the Saturnian plasma and fields environment and enable the study of a magnetospheric system which strongly interacts with other components of the Saturnian system: the planet, its rings, numerous satellites (icy moons and Titan) and various dust, neutral and plasma populations. This very rich magnetospheric environment contains uniquely diverse regions compared with those observed elsewhere in the solar system and a staggering array of magnetospheric phenomena and processes which we are only beginning to comprehend. Understanding the physics of the Saturnian system has been made difficult by the significant temporal variability in the system. By using a multi-instrument approach and studying a significant number of orbits, a better understanding of the spatial structure and physical processes will be gained. The new Cassini data set provides us with a unique opportunity for comparative studies of the saturnian, jovian and terrestrial magnetospheric environments. This will be invaluable to Cassini scientists for providing a framework for further studies of the Saturnian magnetospheric environment and to pull together current knowledge and understanding for the benefit of all planetary scientists.

1. Introduction and Scientific Rationale

Saturn orbits the Sun at 9.5AU, nearly two times further from the Sun as Jupiter and at this distance Cassini data revealed the solar wind to be well-structured into a two-sector configuration, comprising fast and slow streams. Thus Saturn's magnetosphere is subject to pressure rarefactions and compressions at a rate of ~2 per solar rotation, resulting in a highly variable magnetic cavity. At this distance, the solar field has wound-up to form a field inclined at nearly 90° with the Sun-Saturn line, producing a B_Y-dominant upstream field. In addition, the north-south component of the interplanetary magnetic field (IMF) flips back and forth on timescales of minute/hours. This short timescale effect of the field orientation is overlaid onto the longer term dynamic pressure variations from rarefactions/compressions. Finally, the solar wind plasma has expanded and cooled out at this distance, with increased sonic Mach numbers. Therefore, there exist notably different external conditions encasing the Saturnian magnetosphere compared with those at Earth and Jupiter.

The subsolar magnetopause stand-off distance ranges between 16 and 30 R_S (Saturn radius, $1R_S$=60268km) [Arridge et al., 2006] and results in a magnetospheric cavity which is ~15000 times larger than Earth's. Saturn's extensive ring system and many of its moons orbit deep within this giant magnetosphere and provide many opportunities for internal sources of plasma from the surfaces of moons and rings, and in some cases from moon atmospheres [Jurac and Richardson 2005]. The differing ionisation rates between Saturn and Jupiter might also contribute substantially to the observed differences in how the plasma sources are distributed in the magnetosphere.

Saturn is a rapidly rotating planet, with a ~10^h47^m rotation period, and the resulting centrifugal force acts to confine this plasma to the equatorial regions, forming a plasma disc in a similar way to Jupiter [see Sittler et al. 2005, 2006a]. Both planetary rotation and solar wind driving of the magnetospheric dynamics may be operating at Saturn, and recent studies have concentrated on establishing their respective influence [e.g. Cowley et al., 2004; Crary et al., 2005; Sittler et al., 2006b; Gurnett et al. 2007].

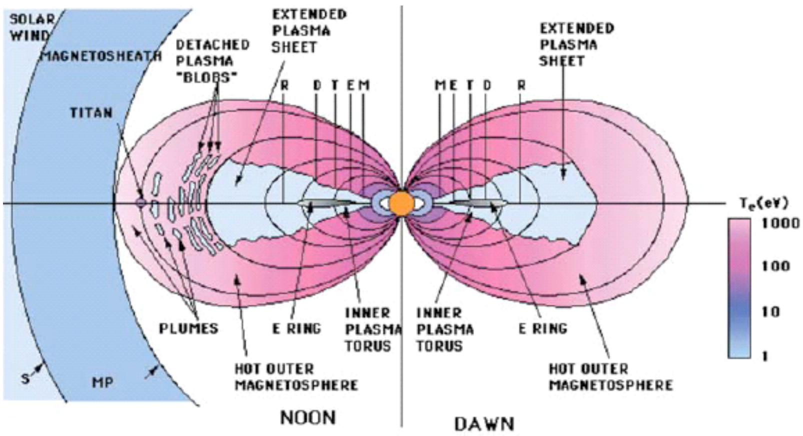

Figure 1 Plasma populations in Saturn's magnetosphere as derived from Voyager data. The left hand side is a composite of the observations made during the inbound leg near noon and the right-hand side from the dawn-midnight quadrant [Sittler et al. 1983]

In terms of comparative magnetospheric science, before the arrival of the Cassini/Huygens mission, Saturn was widely considered as a very interesting intermediate case between Earth and Jupiter [Bagenal, 1992]. Our first view and preliminary understanding of Saturn's magnetosphere was based solely on the fly-by data returned by Pioneer 11 in 1979 and by the Voyager 1 and 2 spacecraft in 1980 and 1981. These observations revealed a magnetosphere partly controlled by its interaction with the solar wind and partly by the rotation of the planet. The magnetosphere appeared to be embedded in a broad neutral cloud of hydrogen and water products with local densities comparable to or significantly larger than the ionised population. A composite of the various plasma populations identified by these missions is shown in Figure 1.

However, the resulting picture was limited by the local time and latitudinal coverage of the fly-bys, lack of ion composition plasma measurements and by the limited energy-angle coverage of the plasma instruments. The dedicated orbital tour of the Cassini mission has provided planetary and space plasma scientists with increased coverage of the magnetosphere over many orbits and an abundance of data leading to deepened and revised interpretations of this picture. Each of the Magnetospheric and Plasma Science (MAPS) [Blanc et al. 2002] instrument teams have based their characterisation and their nomenclature of the various magnetospheric regions encountered by the spacecraft on the particular individual scientific objectives of each instrument. We thus detail here the major regions of the magnetosphere as currently determined, by the Cassini tour to date, with the current labelling adopted by each team. This demonstrates the disparities and similarities between regions and processes identified by the various instruments.

Lobes/High-latitude magnetosphere/quiet magnetosphere
The particle intensities are very low, often below the detection threshold of the thermal plasma instrumentation, with the predominant species being protons. The magnetic fluctuations are weak and the radio wave instrument found this to be pervaded by whistler-mode emission with an as-yet undetermined source.

Outer plasmasphere/plasma sheet/magnetodisc
This region is present between ~12-15 R_S and the magnetopause. Here are high intensities of energetic (~10's keV) particles. Water-group heavy ions are present alongside protons and both have energies close to the corotational energy. The magnetic field in this region is stretched out into a magnetodisc configuration, but on the dayside this configuration can be disrupted under conditions of enhanced solar wind pressure leading to a more quasi-dipolar configuration. Inside the plasma sheet magnetic field fluctuations increase and the field becomes less stretched.

Inner plasmasphere/inner magnetosphere/inner region/the radiation belts
There is a marked change in the characteristics of the plasma and fields within ~10–5 R_S. The highest intensity of energetic particles (0.1 to 1 MeV) is encountered. Inside of around 7.5 R_S ions below 100keV are lost in charge-exchange collisions with the neutral gas cloud. More energetic ions can co-exist with the neutral cloud but this is species dependent; so whilst protons can co-exist with the cloud at 150keV, oxygen ions below ~MeV energies are lost to the cloud and cannot co-exist. However these higher energy ions are absorbed by Saturn's rings and moons. Electrons are also lost in the neutral gas cloud but the more energetic electrons survive immersion in the cloud. Furthermore, Enceladus has been shown to be a primary source of plasma in the inner magnetosphere [Dougherty et al. 2006; Tokar et al. 2006] and modelling of the low-latitude plasma density is consistent with a source at Enceladus and approximately source-free expansion beyond about 5R_S [Persoon et al. 2005, 2006]. The rings themselves are also found to have an oxygen-rich atmosphere.

The high neutral/ion ratio in Saturn's inner magnetosphere makes this region unique in the solar system [Esposito et al. 2005] and understanding its boundaries by energy will be very important. This is a very dynamic region containing plasma injection events and complex wave emissions, where plasma transport operates to redistribute material to the outer regions. The magnetic field adopts a quasi-dipolar configuration within ~ 15 R_S and is almost curl-free inside of 5 R_S. The ionosphere is able to enforce corotation of the low energy plasma which is now dominated by the heavy water-group ions. Two-component electron populations are present at ~ 10's eV and ~ 100's eV [Rymer et al. 2007].

Dust is also a major source of plasma in the E-ring/neutral cloud environment and may contribute significantly to the dynamics of the inner magnetosphere and indeed Saturn's magnetosphere as a whole. Phenomena such as ring-spokes [Mitchell et al. 2006; Jones et al. 2006] and interplanetary dust streams from Saturn [Kempf et al. 2005] highlight the diversity and complexity of dust interactions which need to be considered in any complete description of magnetospheric regions and processes.

This brief overview clearly indicates the need for a more rigorous identification, definition and characterisation of the various regions, their boundaries and the processes they contain. The complex time-variability of the magnetosphere makes the comparison of regions within and between encounters non-trivial. A statistical approach facilitated by comparing many orbits of data will, to some degree, allow the time-averaged structures and processes to be extracted. The interplay of plasma from various origins, their equilibrium and dynamics, and their coupling via transfer of mass, momentum, and energy constitute both observational and theoretical challenges that will be addressed by our team.

2. Proposal and Objectives
The primary objective for this proposal is to provide multi-instrumental identification and characterisation of

magnetospheric regions at Saturn with an emphasis on the physical processes at work in each region and at their boundaries. A comparison of specific magnetospheric processes, such as reconnection, mass-loading/loss, and aurorae with similar processes at Jupiter and Earth is implicit in our proposal. Strong internal plasma sources and rapid planetary rotation lead us to place emphasis on their similarities with Jupiter.

The various different regions and physical processes identified from the pre-Cassini and current missions will be studied keeping the following questions in mind:

1. What are the macroscopic magnetospheric regions?
2. What are the average neutral, plasma, dust, and field properties in these regions?
3. Where do the boundaries of these regions lie?
4. What are the plasma sources, transport processes, and sinks in each region?
5. What are the interactions and physical processes occurring within and between these regions, i.e. current systems, plasma transport, waves and wave-particle interactions, interaction between neutral gas, dust and plasma, and the connection to auroral processes?
6. What are the solar wind and planetary rotational influences on each region?

We plan to use the comprehensive suite of MAPS instruments to give a unified description of the large-scale structure of the Saturnian magnetosphere as emerging from the nominal Cassini mission, both in the equatorial plane and at very high latitudes. We aim to identify the different regions and their boundaries, and characterise in detail the dominant chemical, physical and dynamical phenomena occurring in each of these regions. Data from the magnetometer (MAG), low-energy spectrometers (CAPS), energetic particles detectors (MIMI), radio and plasma wave (RPWS), and cosmic dust analyser (CDA) instruments will be considered and analysed in detail in order to address our main scientific objectives. We will use a combination of results from both theoretical modelling and simulations to enable a strong synthesis and provide distinctions between the current emerging views of the Saturnian system.

Our team consists of scientists from around the world, each bringing unique expertise to the project. Many of the team members worked with the Pioneer, Voyager and Galileo data at Jupiter and Saturn before becoming involved within the Cassini mission. Our team adequately combines researchers involved in each of the main MAPS instrumental teams listed previously, and will benefit from strong interactions with other researchers having developed either large-scale simulations of planetary magnetospheres or theoretical approaches to understand the critical mechanisms operating in these systems. Dust is an important constituent of Saturn's magnetosphere and our proposal also represents one of the first efforts to combine dust observations with the results from fields and particles instrumentation to produce a unifying synthesis.

3. Expected Output and Project Schedule

The primary objective for this proposal is to provide a multi-instrumental characterisation and description of magnetospheric regions and processes at Saturn. We envisage a series of review articles describing our findings on each magnetospheric region and an overview article which provides our unifying conceptual view for Saturn's magnetosphere and containing the results of our global mapping and integration. We will also provide a working synthesis 'map' freely available to the Cassini community, which we will continue to refine as our understanding develops. To achieve our goals and answer the broad science questions set out in the introduction we have identified three phases to this proposal:

Phase 1 (duration=6 months) [Start August 2007]
During phase one we will collate from each team member and instrument their definition of different regions of the magnetosphere the location of the boundaries between regions, any specific variability, and the broad physical processes in these regions. This will facilitate an assessment of the discrepancy between instrumental views and allow particular focus to be set on particular areas of Saturn's magnetosphere.

We will bring these data together into a global map depicting the various regions and processes, and where they overlap, and provide a set of regions with a unified nomenclature with which to work on. From this synthesis we will split the team into working groups to study and characterise each region. The key deliverable from this preliminary phase will be a scientific document, made available to the whole Saturn magnetospheric community, which will act as a global scale map and reference guide for Saturn's magnetosphere.

Phase 2 (duration=12 months) [Start February 2008]
During the main phase of the project each region will be studied in detail by the various working groups, with the aim of addressing each of our six broad science questions. During this process our map and reference guide will be continually updated so that we can refine the definition and description of each region and the boundaries between them. To ensure continuity between working groups we will consider the degree of spatial overlap so that transitions between regions can be studied and better understood.

The key deliverables from phase two are review articles, one from each working group, describing and characterising the physical processes, location, and variability of each region. We fully expect such a review article to be written concurrently with science articles describing recent findings of direct relevance to the proposal. Also during phase two there will be a Cassini PSG (Project Science Group) meeting in Rome (2008) which coincides with the end of the nominal Cassini mission. This presents an ideal opportunity to highlight our preliminary findings and provide further input to the design and refinement of the Cassini extended mission.

Phase 3 (duration=6 months) [Start February 2009]
The final phase of our study will be to compare and contrast our findings with our current knowledge of the jovian and terrestrial magnetospheres and to attempt to address the question in the title of our proposal. As the final phase of our proposal it allows us to bring together our increased understanding of Saturn's magnetosphere and to address a particularly focused question, which has been asked since before Cassini was launched, is Saturn's magnetosphere Earth-like or Jupiter-like, or 'Saturn-like'.

To coincide with these phases we plan on two week-long meetings at ISSI: a start-up meeting provisionally set for 27-31 August to directly follow the European Planetary Science Congress in Potsdam, and a phase two meeting provisionally set for 1-5 September 2008. We anticipate full team attendance at these ISSI meetings. To ensure proper progress and to facilitate communication we also plan on holding one day meetings at the AGU Fall Meeting, San Francisco in December of 2007 and 2008, and also the EGU General Assembly, Lyon in April of 2008 and 2009. Our December 2008 meeting in San Francisco will essentially mark the end of phase two and will allow us to focus our understanding and efforts for the final phase of the proposal. As we have commented, the Cassini PSG meeting in Rome during the summer of 2008 will also allow us to present our preliminary findings.

The timetable for our expected output is as follows:
February 2008: Synthesis map and reference guide for Saturn's magnetosphere. Working document for open release to the Cassini community and made available through our ISSI Project website.
February 2009: Review articles for Space Science Reviews or Reviews of Geophysics describing the processes and regions in Saturn's magnetosphere. We expect 3-5 articles depending on the number of regions we divide the magnetosphere into. We also expect to write an overall review article pulling our findings together and to formalise the synthesis map document we prepared at the end of phase one.
August 2009: Review or science article comparing and contrasting the saturnian, jovian, and terrestrial magnetospheres.

4. Timeliness and reasons for choosing ISSI
In just under three years into the mission, the coverage of the magnetosphere afforded by the Cassini tour is unparalleled for an interplanetary mission of this type (see figure 2). As the extended mission begins in July 2008, the additional coverage at higher latitudes and in the pre-noon sector places the team in a unique position to work on integrating data from much of the magnetosphere, thus providing a truly global synthesis of the plasma and field characteristics at Saturn. In this proposal we hope to act as enablers, facilitators and catalysts in the process of scientific discovery so that major advances can be made speedily while the attention of the planetary community at large is still on Cassini and Saturn's magnetosphere.

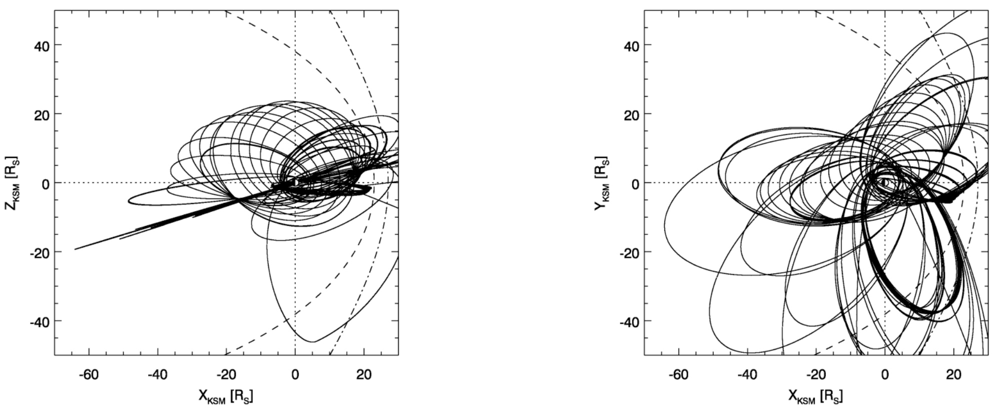

Figure 2 Cassini's nominal tour projected in the KSM X-Z (noon-midnight, left) and KSM X-Y planes (right) with model magnetopause (dashed) [Arridge et al. 2006] and bow shock (dot-dash) [Slavin et al. 1985] surfaces.

The use of the ISSI facilities will enable a location for the international scientists to gather and exchange ideas in a focused and distraction-free environment not always possible at other meetings and conferences. Having accessible internet-enabled work stations, with which to utilise instrument-specific tools available to team members, will enable a productive, real-time working environment.

5. List of confirmed participants

We have 15 confirmed team participants drawn from each instrument team on Cassini. Our team leader is Chris Arridge at MSSL/UCL in the UK with Hazel McAndrews (soon to be at LANL in the USA) and Nicolas André (RSSD/ESTEC) as deputy team leaders. Table 1 lists our team members. Our team will also use an external consultant, Thomas W. Hill (Rice University, USA), and the proposal will benefit greatly from Dr. Hill's experience in theory and modelling of giant planet magnetospheres.

Table 1 List of team members, institutions, countries and team affiliations

Team Member	Institution	Country	Cassini MAPS Team Affiliation
Christopher S. Arridge	MSSL/UCL	UK	CAPS/MAG
Hazel J. McAndrews	MSSL/UCL[1]	UK[1]	CAPS
Nicolas André	RSSD/ESTEC	The Netherlands	MAPS IDS Team / CAPS
Emma J. Bunce	SRC/U. Leicester	UK	MAG
Kenneth C. Hansen	AOSS/U. Michigan	USA	MAPS IDS Team
Robert E. Johnson	U. Virginia	USA	CAPS
Geraint H. Jones	MSSL/UCL	UK	CAPS
Sascha Kempf	MPK	Germany	CDA
Krishan K. Khurana	IGPP/UCLA	USA	MAG
Norbert Krupp	MPS	Germany	MIMI
William S. Kurth	U. Iowa	USA	RPWS
Christopher Paranicas	JHU-APL	USA	MIMI
Christopher T. Russell	IGPP/UCLA	USA	MAG
Edward C. Sittler	GSFC/NASA	USA	CAPS
Michelle F. Thomsen	LANL	USA	CAPS

GSFC/NASA: Goddard Space Flight Centre, IGPP/UCLA: Institute of Geophysics and Planetary Physics, University of California Los Angeles, MSSL/UCL: Mullard Space Science Laboratory, University College London, MPS: Max-Planck-Institut für Sonnensystemforschung, RSSD/ESTEC: Research and Scientific Support Department, ESTEC, ESA, JHU-APL: Johns Hopkins University Applied Physics Laboratory, SRC/U. Leicester: Space Research Centre, University of Leicester, AOSS, U. Michigan: Department of Atmospheric, Oceanic and Space Physics, University of Michigan, MPS: Max Planck Institute for Solar System Research, MPK: Max Planck Institute for Nuclear Physics, LANL: Los Alamos National Research Laboratory, IDS: Inter-disciplinary scientist.

[1] Soon to be at Los Alamos National Research Laboratory, New Mexico, USA

6. Facilities required

Since all participants will provide their own laptops and data analysis software only a wireless-enabled meeting room will be required. The room will need to seat 15 and have a data projector and projector screen. Multiple power points will also be required.

7. Financial support from ISSI

Item	Cost
Team coordinator travel to 2 meetings	2400 €
T&S for 15 members x 5 days x 2 meetings	150 per diems (30000€ at 200€ for each per diem)
Total	**32400€**

APPENDIX 1 - References

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APPENDIX 2 CONTACT DETAILS FOR ALL PARTICIPANTS

Team Member	Postal Address
Christopher S. Arridge	Mullard Space Science Laboratory, Department of Space and Climate Physics, University College London, Holmbury St. Mary, Dorking, Surrey, RH5 6NT, UK
Hazel J. McAndrews	Mullard Space Science Laboratory, Department of Space and Climate Physics, University College London, Holmbury St. Mary, Dorking, Surrey, RH5 6NT, UK
Nicolas André	Research and Scientific Support Department, European Space Agency, Keplerlaan 1, 2200 AG, Noordwijk, The Netherlands
Emma J. Bunce	Space Research Centre, Department of Physics and Astronomy, University of Leicester, University Road, LE1 7RH, UK
Kenneth C. Hansen	1411D Space Research Building, University of Michigan, 2455 Hayward St., Ann Arbor, MI, 48109-2143, USA
Robert E. Johnson	Materials Science and Astronomy Departments, Thornton Hall B103, University of Virginia, Charlottesville, VA 22904, USA
Geraint H. Jones	Mullard Space Science Laboratory, Department of Space and Climate Physics, University College London, Holmbury St. Mary, Dorking, Surrey, RH5 6NT, UK
Sascha Kempf	Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany
Krishan K. Khurana	Institute of Geophysics and Planetary Physics, University of California at Los Angeles, Los Angeles, CA, 90095, USA
Norbert Krupp	Max-Planck-Institut für Sonnensystemforschung, Max-Planck-Str. 2, D-37191, Katlenburg-Lindau, Germany
William S. Kurth	Dept. Physics & Astronomy, University of Iowa, Iowa City, IA 52242, USA
Christopher Paranicas	Applied Physics Laboratory, The John Hopkins University, Laurel, MD 70723, USA
Christopher T. Russell	Institute of Geophysics and Planetary Physics, University of California at Los Angeles, Los Angeles, CA, 90095, USA
Edward C. Sittler	NASA/GSFC, Code 673, Greenbelt, MD 20771, USA
Michelle F. Thomsen	MS D466, Los Alamos National Laboratory, Los Alamos, NM 87545, USA

APPENDIX 3 – Curriculum Vitae for the team members