Title: Investigating the Dynamics of Planetary Magnetotails

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Young scientists to be contacted after proposal accepted.

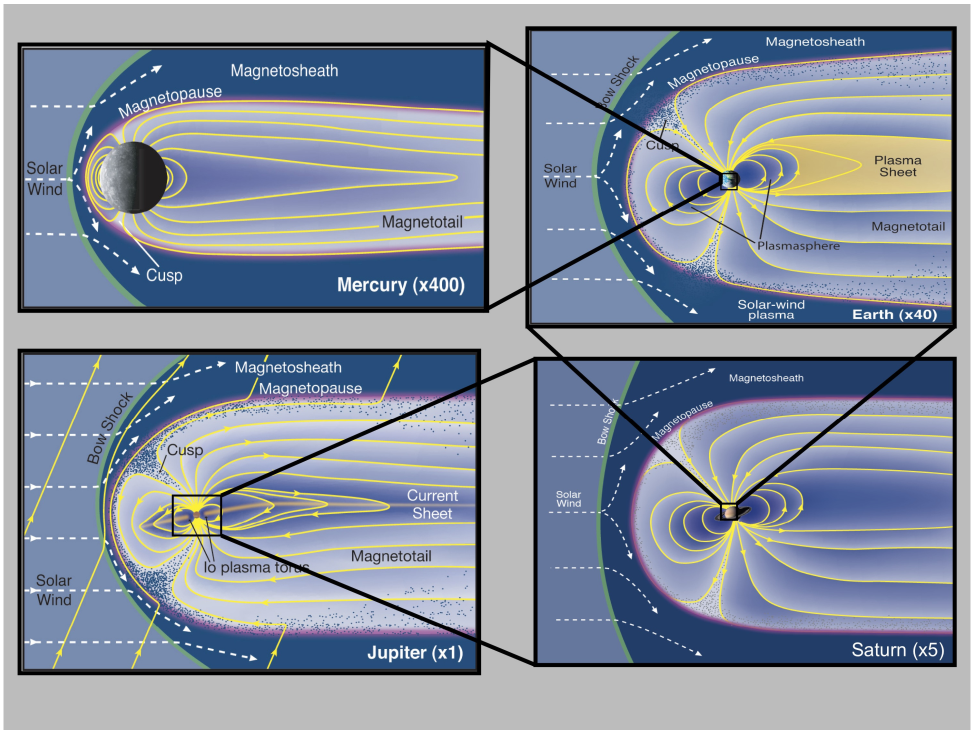
Abstract
Spacecraft observations have established that all magnetised planets interact strongly with the solar wind and possess well-developed magnetic tails. We wish to study reconnection, convection, and charged particle acceleration in the magnetic tails of Mercury, Earth, Jupiter and Saturn. These fundamental physical processes are common to all these planetary environments and relate to a complex chain of events that ultimately release mass and energy in magnetised configurations. The great differences in solar wind conditions, planetary rotation rates, ionospheric conductivity, and physical dimensions from Mercury's small magnetosphere to the giant magnetospheres of Jupiter and Saturn, provide an outstanding opportunity to extend our understanding of the influence of these factors on these basic processes. We will draw together data analysis experts and global modellers to build up a full picture of small- and large-scale dynamics. We will make use of numerous data sets from MESSENGER, Geotail, Cluster, THEMIS, Galileo, New Horizons, Cassini, and the Hubble Space Telescope (HST) to name but a few, together with sophisticated simulation and modelling tools in order to probe in-situ and remotely the deep magnetotails of these planets.

1. Introduction and Scientific Rationale

Planetary magnetotails are the site for many dynamic changes critical to the circulation of mass and magnetic flux and the acceleration of charged particles. The slowly rotating magnetospheres at Earth and Mercury possess magnetic tails which are the site of the energy storage and release that drives a solar wind-controlled convection cycle. Meanwhile, plasma circulation in the magnetospheres of Jupiter and, to some extent, Saturn is driven by centrifugal forces due to rapid planetary rotation. Further, the extent and composition of the ions added to these magnetic tails by the atmospheres of these planets and their satellites are very different as are the rate and manner of their thermalization and the importance of finite Larmor radius effects. Despite all of these different boundary conditions and drivers, magnetic reconnection, plasmoid ejection, and charged particle acceleration take place in all of these magnetotails. We propose to dedicate an ISSI Team to the comparative examination of the magnetic tails of Mercury, Earth, Jupiter and Saturn (shown in Figure 1) for the purpose of better understanding the influence of such factors on tail processes.

Magnetic reconnection is a fundamental physical process that can release energy and mass that has built up inside magnetotails. The processes by which magnetospheres accumulate mass are very different, and we expect that the processes by which this mass is lost will also prove to be incredibly diverse. Nonetheless, the fundamental process of magnetic reconnection is the same. At the reconnection X-line, oppositely directed field lines come together, break, and then merge to form new field lines, as shown in Figure 2. Planetward of this reconnection site, newly dipolarised field lines rapidly contract back toward the planet. Accelerated charged particles (e.g. electrons) can precipitate along these closed field lines and the auroral response to such particles can be dynamic and varied. Meanwhile, tailward of the reconnection point, plasmoids are released and begin to move rapidly downtail.

Figure 1: Comparison of the magnetospheres of Mercury, Earth, Saturn and Jupiter.



Most diagrams of magnetospheres end shortly beyond the reconnection region, with little or no description of the evolution of plasmoids tailward of this, despite the key role that plasmoids play in the ejection of mass from magnetospheres. We intend to address this point, drawing together the common physical principles that underpin the process of energy loss from the magnetotails of Mercury, Earth, Jupiter and Saturn, and highlighting the contrasting characteristics. We will examine the global response through deep tail analyses of plasmoid evolution, close-up analysis of X-region properties, and remote sensing of the response of the auroral regions. Each of these planetary magnetospheres has its own individual and unique characteristics, and some of the important parameters are listed in Appendix 1 (Table 1). Aside from their size, these magnetospheres are affected to a large extent by vastly different planetary rotation rates, external solar wind influences and internal plasma production rates. But the physical process of magnetic reconnection is common to all, and by taking a comparative approach to a number of specific science questions, we can develop a greater understanding of the dynamics in these fascinating environments.

2. Comparative magnetosphere approach and key questions addressed

The processes leading to a loss of equilibrium in the magnetotail and the onset of magnetic reconnection have been well studied in the terrestrial magnetosphere, with a clear sequence of events mapped out since the 1960s [Akasofu, 1964] but with considerable controversy over the exact timing of events [e.g., Ohtani, 2001]. Earth's magnetospheric dynamics are dominated by the effects of the solar wind and recent work is uncovering the role that the interplanetary magnetic field direction plays in triggering the onset of magnetotail reconnection [Milan et al., 2007; Freeman and Morley, 2009]. Jupiter's magnetosphere, the archetype of a fast rotating magnetosphere, has a magnetotail that can stretch to the orbit of Saturn [Scarf et al., 1982], and data from the Galileo spacecraft has revealed a magnetotail reconnection process which is linked to mass loading from the volcanic moon Io and rotation rate dynamics [Kronberg et al., 2007]. Recently the New Horizons spacecraft has flown down much of the length of the jovian tail, and the dataset can tell us about the structure of the very distant regions, as well as the evolution of plasmoids [McComas et al., 2007]. Saturn, which lies nine times further away from the Sun than Earth, is also affected to some degree by the solar wind, but rapid planetary rotation combined with internal plasma sources (for example, Enceladus) make the saturnian system a more complex target, albeit one made accessible with the fantastic data which the Cassini spacecraft has taken since 2004. Cassini traversals of Saturn's magnetotail have revealed evidence of magnetic reconnection [Jackman et al., 2007], but many questions regarding the driving mechanisms and global response remain unanswered. Finally, the Sun's nearest neighbour Mercury possesses a "mini-magnetosphere", at times barely able to hold off the bombardment of the solar wind, but with a well-defined magnetotail nonetheless, and evidence of a reconnection and plasmoid release via an X-type geometry [Slavin et al., 2009]. With several previous spacecraft flybys and the scheduled arrival of the NASA Messenger mission into orbit in March 2011, Mercury is too good a target to miss in our exploration of comparative magnetotail dynamics.

We plan to draw on techniques developed at Earth, along with the wealth of multi-spacecraft data from missions such as Geotail, Cluster and THEMIS, to compare and contrast knowledge from our best-sampled environment to the less explored magnetospheres of our solar system. Our study of the interior of these magnetospheres will be greatly enhanced by the addition of remote auroral information (they are numerous at Earth, and very valuable at Jupiter and Saturn with dedicated observational campaigns from HST and other spectro-imagers, e.g., Cassini UV Imaging Spectrometer), combined with knowledge of the surrounding solar wind, from data and models (e.g., Michigan Solar Wind Model or CCMC).

Our top level aim is to use observations and modelling of magnetotail equilibria and dynamics in order to develop a deeper understanding of the dynamics of planetary magnetotails. This aim drives three main science questions which we plan to address.

2.1 What drives magnetotails from equilibrium to instability?

Plasmoids and newly-dipolarised field lines have been observed in the magnetotails of Earth, Jupiter, Saturn and Mercury, providing direct evidence for reconnection processes. However, much remains to be understood about the precise drivers of reconnection. What are the processes that trigger periods of reconnection? We plan to examine aspects such as changes in external solar wind conditions, magnetotail magnetic field line geometry, magnetotail flux and mass content, as well as the role of mass-loading from internal sources and the influence of planetary rotation through a combination of in situ data analysis (case studies and statistics), and modelling.

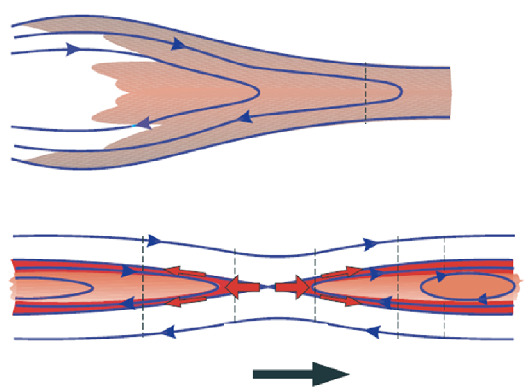


Figure 2: Schematic diagram of the x-point reconnection site, with the associated field reconfiguration and plasma flows [Kronberg et al., 2005].

We will take a statistical approach to decipher the typical x-line position in the different magnetotails. Vogt et al. [in press, 2010] looked at reversals in magnetic field direction (and corresponding plasma flow) at Jupiter to build up a catalogue of which side of the reconnection site the spacecraft (Galileo) was on at any given time. We will adapt this same technique to Saturn and Mercury to map where the transition region is and then further study how this location is determined by the degree of field line distortion, or the magnetotail total flux content.

We will also adapt models such as the Minimal Substorm Model [Freeman and Morley, 2004] which is a simple statistical model developed for Earth to predict the timing of substorm events. With knowledge of appropriate input parameters such as solar wind conditions, mass loading rates, and average X-region positions, we can build increasingly realistic models of global magnetospheric response to nightside processes. We have access to the vital tools for such work, in the form of sophisticated solar wind propagation models [e.g. Zieger and Hansen, 2008; Zieger et al., 2009] which allow us to understand the environments in which these planets are immersed. We will also draw on the success of global 3D numerical MHD models such as those developed for Saturn [e.g., Fukazawa et al., 2007; Kidder et al., 2009; Hansen et al., 2009], Jupiter [e.g., Fukazawa et al., 2006], and Mercury [e.g., Kidder et al., 2008]. Such modelling work can allow us to output data time series from virtual spacecraft which can then be compared directly with in situ observations. In this way we can see which aspects of the reconnection process are common to the different magnetospheres, and which aspects require uniquely tailored modelling techniques to accurately represent their contrasting features.

2.2 What are the characteristics of the distant magnetotail?

As mentioned in Section 1, most diagrams of magnetospheres end shortly beyond the reconnection point. A key aim of our work is to explore the structure of deep magnetotails and fill in this gap in magnetospheric knowledge through the use of recent data, in particular from the Geotail spacecraft out to ~210 R_E at Earth, and the New Horizons spacecraft which flew ~2500 R_J down the jovian tail. How coherent is the magnetotail out to large distances? Is there any effect with heliocentric distance or planetary/magnetospheric parameters?

The study of plasmoids in the distant tail and their evolution allows us to also examine the mass-loss process. How is the mass that is pinched off at the reconnection point ultimately lost back into interplanetary space? Is this mass lost as large single chunks or as long chains of smaller plasmoids? For this aspect of our work we will draw on the expertise of a number of members of the team to undertake flux rope fitting and Grad-Shafranov reconstruction-type techniques originally developed for use with multi-spacecraft data at Earth. We can complete 2-D reconstructions of plasmoids in order to establish their shape, speed, length, plasma and flux content, and thus understand their role in the flux cycle at the different planets.

2.3: What happens planetward of the reconnection point – auroral response

Planetward of the reconnection point the tension in the previously-stretched field lines is released as kinetic energy and closed field lines dipolarise and are rapidly accelerated back toward the planet. Precipitation of energetic electrons along these field lines can lead to dynamic responses from ultraviolet and infrared aurorae. At Earth and Jupiter, the intensity and morphology of the UV aurora can change dramatically in response to tail processes [e.g. Boudouridis, et al., 2003; Radioti et al., 2008]. The size of the polar cap, as extracted from auroral images can be used to calculate the amount of open flux contained within the terrestrial magnetotail [Milan et al., 2003]. Thus far, this technique has been shown to be applicable for Saturn [Badman et al., 2005] and we plan to expand on this idea with the wealth of HST data and in situ spectral imaging now available from Cassini. Pulsations in the jovian aurora have been used to infer reconnection rates in Jupiter’s tail [Radioti et al., 2008]. However, at Jupiter (and indeed the more mixed magnetosphere of Saturn), debates rage as to the release mechanism for stored-up plasma with some arguing for a “drizzle” of mass down the tail as opposed to the breaking off of large plasmoids periodically [Bagenal, 2007]. By drawing together both in situ and remotely sensed datasets, and team members with varied expertise in this area, we can objectively tackle questions such as these.

Kilometric radio emissions can also respond dynamically to magnetotail processes, through intensifications and also changes in the frequency of the emission, as has been shown at Earth and Saturn [Morioka et al., 2008; Jackman et al., 2009]. The huge advantage of exploiting radio emission data is that, unlike the in situ plasmoid or dipolarisation signatures, radio emissions can be remotely sensed from anywhere and thus are an excellent diagnostic of tail conditions – if we can understand the radio characteristics properly. A key aim of our work on this section is to synthesise our knowledge of radio emissions at Saturn, Jupiter and Earth to understand the timescales between reconnection and radio response, and to establish whether or not there is a 1:1 correlation between specific radio signatures and magnetotail events.

Aside from the response of the auroral zones to reconnection in the tail, on a more local scale we will explore how particles are accelerated and heated near the reconnection site. How can our knowledge from Earth be applied to explain energisation observations at Jupiter, Saturn and Mercury? Data from Galileo at Jupiter has shown that heavy ions are very efficiently energised during magnetotail reconnection, and that this can account for previously unexplained composition data from the energetic particles detector instrument [Radioti et al., 2007]. This work drew on a model initially proposed for Earth's magnetotail [Delcourt et al., 1997], yet another illustration of how the same physics can be applied in different environments, expanding the parametric range of models. Our work will focus on identifying the specific acceleration mechanisms that are responsible for periodic energetic particle distributions at Jupiter, and for those at Saturn and Mercury also. How can acceleration and heating from a small X-line region affect the magnetosphere on a global scale?

3. List of the expected output e.g., papers, reviews

We plan a review paper of comparative magnetotail dynamics. We will develop a model of plasmoid formation, though the original adaptation of flux-rope fitting and Grad Shafranov reconstruction techniques from Earth to Jupiter, Saturn and Mercury to compare and contrast the morphology of mass release there. We will draw together remote sensing and in situ data to explain the relationship between magnetotail reconnection and auroral emissions at the first three planets. We will review and advance our understanding of the structure of distant magnetotails, far beyond the X-line region, as well as determining the statistical location of this X-region.

4. Timeliness and reasons for choosing ISSI

We are currently at a key point in the exploration of planetary magnetotails. At Earth, data from the multi-spacecraft Geotail, Cluster and THEMIS missions are providing a never-before-possible look at the intricate details of magnetotail processes at small and large scales. At Jupiter, the analysis of new data from the New Horizons spacecraft is still in its relative infancy, and the current preparation of future missions (Juno, EJSM) to the planet attracts considerable and renewed interest for Galileo data. At Saturn, the Cassini spacecraft is entering its second mission extension to explore beyond equinox toward solstice. Lastly, the NASA MESSENGER mission is set to go into orbit in Mercury's mini magnetosphere in March 2011, following its successful three flybys of the planet. There has never been a better time to undertake a multi-mission comparative study of magnetotail processes in these very different environments. This ISSI Team will provide us with a chance to bring together people from very different communities who can all contribute to our joint aim, but who would not otherwise encounter each other for collaboration.

5. Schedule of the project,

We expect to hold two meetings for one week each. The suggested date for the first meeting is late September 2010, while we plan the second meeting for summer 2011, subject to schedules. We also plan to take advantage of large conferences such as the Fall AGU meeting and the EGU meeting to have brief group meetings to discuss science progress.

6. Facilities and financial support required of ISSI:

We expect that all participants will provide their own laptops, so we just require a room with wireless internet access, a data projector and screen. We also require hotel and subsistence costs for 12 team members at two team meetings at ISSI, and hotel, travel and subsistence costs for the team leader to attend both meetings. These costs are detailed in the table below. We would also request funding for young scientists to attend select meetings – these will be invited if our proposal is accepted.

Travel costs for team leader to travel to two team meetings	€700
Hotel and subsistence costs for 12 team members to attend two team meetings: 12 members x 5 days x 2 meetings @ €200	€24 000
Total	**€24 700**

Appendix 1: Table

Parameter	Saturn	Jupiter	Earth	Mercury
Equatorial planetary radius (km)	60268	71492	6371	2440
Surface field strength (nT)	21084	420000	32000	340
Dipole moment (A m^2)	4.6×10^{25}	1.5×10^{27}	8.3×10^{22}	4.9×10^{19}
Sidereal rotation rate (hh:mm)	~10:48?	09:55	23:56	1407:30
Average solar wind D_p (nPa)	0.03	0.08	2	20
IMF field strength (nT)	0.6	1	8	30
Average IMF parker angle	83	80	45	20
Tail radius (R_p)	60	150	30	2-3
Tail lobe flux content (GWb)	~15-50	100s	0.2- 1	0.003
Average MP standoff distance (R_p)	23	84	10	1.4
SW transit time to tail (min)	120	360	5.3	2.8

Table 1: List of planetary and magnetospheric parameters, organised by decreasing distance from the Sun

Appendix 2: List of confirmed members.

Team member	**Institution**	**Country**	**Expertise**
Caitriona Jackman	ICL	UK	Cassini MAG
Chris Arridge	MSSL/UCL	UK	Cassini MAG/CAPS
Nicolas Andre	CESR	France	Cassini MAPS
Fran Bagenal	LASP, U. Colorado	USA	Voyager PLS, Galileo IDS, Deep Space 1, New Horizons, Juno
Joachim Birn	LANL	USA	Global MHD Modelling
William Farrell	NASA/GSFC	USA	Voyager, Cassini RPWS, WIND, DSX
Mervyn Freeman	BAS	UK	SuperDARN, Substorm models
Xianzhe Jia	U. Michigan	USA	Cassini IDS, Global MHD Modelling
Steve Milan	U. Leicester	UK	SuperDARN, CUTLASS, KuaFu-B, Bepi-Columbo
Aikaterini Radioti	U. Liege	Belgium	HST, Cassini UVIS, Galileo EPD
James Slavin	NASA/GSFC	USA	MESSENGER, MMS, Bepi-Columbo, Cluster, WIND
Martin Volwerk	OEAW	Austria	Galileo MAG/Cluster FGM/THEMIS FGM

ICL: Imperial College London
MSSL/UCL: Mullard Space Science Laboratory, University College London
CESR: Centre d’Etude Spatiale des Rayonnements
LASP/U. Boulder : Laboratory for Atmospheric and Space Physics, University of Colorado
IDS: Inter-disciplinary scientist
LANL: Los Alamos National Research Laboratory
NASA/GSFC: Goddard Space Flight Centre
BAS: British Antarctic Survey
U. Michigan: University of Michigan
U. Leicester: University of Leicester
U. Liege: University of Liege
OEAW: Osterreichische Akademie der Wissenschaften

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