MHD Simulations of Current Systems in Planetary Magnetospheres: Mercury and Saturn

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The study of planetary magnetospheres can provide valuable insight into a wide range of phenomena and processes acting in the terrestrial magnetosphere. This paper uses global MHD simulations to investigate the large scale configuration and current systems in two very different planetary magnetospheres. Mercury has a weak intrinsic magnetic moment and it is exposed to a high density, very variable solar wind. It has no ionosphere or plasmasphere and its slow rotation is unimportant. Under typical conditions in the solar wind, Mercury’s magnetosphere is very “open”, the last closed field-line being at a latitude of 40°–50°. At the other end of the spectrum, the interplay between solar wind and planetary rotation driven processes, combined with strong plasma sources, generates new and interesting configurations and current systems in the magnetosphere of Saturn. In particular, our simulations predict two current systems connecting plasma sources in the rings/icy satellites region and in Titan’s torus to the high-latitude regions of Saturn’s ionosphere.

1. INTRODUCTION

The planets Mercury, Earth, Jupiter, Saturn, Uranus and Neptune possess significant intrinsic magnetic fields. Since the underlying plasma-physical processes are the same in these magnetospheres, qualitative or quantitative analogies with the terrestrial magnetosphere can help us to understand poorly sampled planetary magnetospheres. Conversely, similarities in planetary magnetospheres, in spite of differences in configurations, plasma and energy sources and sinks, can help us to understand better the full range of phenomena and processes in the Earth’s magnetosphere. Planetary magnetospheres help us to extend observed magnetospheric phenomena into different parameter regimes. The study of magnetospheric current systems is a very powerful tool in gaining a global perspective of the multiscale coupling between various regions in planetary magnetospheres.

In this paper we investigate the large-scale magnetospheric configuration and associated current systems in two vastly different planetary magnetospheres. Among magnetized planets Mercury has the weakest intrinsic magnetic field (its magnetic moment is about 3,000 times smaller than the terrestrial magnetic moment), while Saturn’s magnetic moment is the second largest among all solar system planets (580 times larger than the magnetic moment of Earth). Magnetospheric current systems in these two planetary magnetospheres clearly exhibit many of the most interesting features relevant to Earth and many astrophysical magnetospheres.

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This paper uses global MHD simulations to study the large-scale configuration of the Hermean and Kronian magnetospheres. The high performance BATS-R-US simulation code has been developed at the University of Michigan and it solves the equations of ideal magnetohydrodynamics on an adaptively refined grid [Powell et al., 1999]. The code has been successfully used to simulate solar system plasmas ranging from the 3D expansion of solar wind [Groth et al., 1999] to the interaction of the heliosphere with the magnetized interstellar medium [Linde et al., 1999], to the magnetospheres of Earth [Gombosi et al., 1998; 1999], Venus [Bauske et al., 1998], Saturn [Hansen et al., 1998], comets [Gombosi et al., 1996; Härler et al., 1997], and to the magnetospheric interaction of planetary satellites, such as Io [Comb et al., 1998], Europa [Kabin et al., 1998a] and Titan [Kabin et al., 1998b].

2. MODEL

The BATS-R-US (Block Adaptive-Tree Solar-wind Roe-type Upwind Scheme) code solves the governing equations of ideal magnetohydrodynamics. The high-resolution finite volume solution scheme is based on an approximate Riemann solver for magnetohydrodynamics [Powell, 1994; Powell et al., 1995]. In this approach, the hydrodynamic and electromagnetic effects are solved for in a fully three-dimensional tightly coupled manner, rather than in separate steps [Gombosi et al., 1994; Powell et al., 1995; 1999].

The code uses a limited reconstruction that ensures second-order accuracy away from discontinuities, while simultaneously providing the stability that ensures nonoscillatory solutions. In addition, the code employs two accurate approximate Riemann solvers: the Roe [1981] scheme [Powell, 1994] and the Linde [1998] solver. The resulting scheme works equally well across a range of several orders of magnitude in plasma \( \beta \) (\( \beta \) is the ratio of the kinetic and magnetic pressures).

The basic data structure used in the BATS-R-US approach is that of adaptive blocks [Stout et al., 1997; Powell et al., 1999]. Adaptive blocks partition space into regions, each of which is a regular Cartesian grid of cells, called a block. If the region needs to be refined, then the block is replaced by 8 child subblocks (one for each octant of the parent block), each of which is a Cartesian grid of cells containing the same number of cells as the parent block. If coarsening is needed, then the 8 children are replaced by their parent. The blocks in the grid, at their various levels of refinement, are stored in a tree data structure.

BATS-R-US was specially designed to handle objects with strong intrinsic magnetic fields. It achieves improved solution accuracy by solving for \( B_1 \), which is the measure of the deviation of the full magnetic field from the intrinsic field, \( B_0 \), and is defined as \( B_1 = B - B_0 \). This approach was first employed by Ogino and Walker [1984] and Ogino [1986] (and later applied to Godunov-type schemes by Tanaka [1995]) and can lead to improved numerical solutions by alleviating the necessity of resolving the often large spatial gradients associated with the intrinsic fields and by ensuring that the divergence of the intrinsic component of the magnetic field is by definition zero. Note that in this formulation \( B_1 \) does not have to be small, therefore this decomposition is completely general.

3. MERCURY

Mercury’s magnetosphere is surprisingly poorly studied, and consequently, poorly understood. It has been visited only by Mariner 10, which encountered Mercury three times between March 1974 and March 1975 (however, one of the three encounters was so far upstream that it completely missed the magnetosphere).

The first estimate of Mercury’s magnetic moment was between 284 and 358 nT \( R_M^2 \) [Ness, 1975]. However, the poor spatial coverage during the two magnetospheric flybys of Mariner 10 make the evaluation of the intrinsic moment of Mercury very complicated and the results are highly dependent on the physical assumptions [Ness, 1975; Connerney and Ness, 1988].

A tenuous atmosphere was observed at Mercury by the Mariner 10 spacecraft [Broadfoot et al., 1976]. This atmosphere is mainly composed of hydrogen, helium and oxygen, with traces of sodium and potassium. The H, He, and O components are thought to be of solar wind origin, while sodium and potassium atoms are probably produced by sputtering [Lammer and Bauer, 1997]. The total column density of the neutral atmosphere is estimated to be less than 10\(^{12}\) cm\(^{-2}\), which is essentially negligible from the perspective of magnetospheric interaction. In the Mercury simulations shown in this paper all atmospheric effects are neglected.

In our simulation Mercury was approximated by a solid nonmagnetic sphere with a radius of \( R_M = 2,440 \) km. The intrinsic magnetic field was approximated by a dipole moment of 330 nT \( R_M^3 \), with the magnetic moment vector pointing south (the same sense as Earth). The surface conductivity was assumed to be zero, thus neglecting the effects of a photoelectron sheath which may form around Mercury [Grard, 1997]. Magnetic flux was allowed to cross the surface of the planet, but no particle flux could penetrate the surface. The boundary conditions on the surface were imposed by utilizing cut cells [DeZeeuw and Powell, 1992], which allows second order (piecewise linear) reconstruction of the boundary geometry.
The upstream plasma flow conditions around Mercury may vary significantly depending on several factors, including the position of the planet on its trajectory and solar activity. In this paper we present simulations for "typical" solar wind conditions near perihelion: \( n = 73 \text{ cm}^{-3}, \)
\( T = T_e + T_i = 14 \text{ eV}, B = 46 \text{ nT}, u = 430 \text{ km/s}, \)
ion-acoustic sound speed \( a = 74.2 \text{ km/s}, \)
Alfvén speed \( V_A = 120 \text{ km/s}, \)
mean molecular mass \( \sim 1 \text{ amu}, \)
and specific heat ratio \( 1.67. \)
The corresponding ion-acoustic Mach number is 5.8 and Alfvénic Mach number is 3.6. At Mercury's orbit the Parker spiral magnetic field forms an angle of 20° with the solar wind direction. However, we must emphasize that these parameters may vary significantly. A parametric study of the effect of various solar wind conditions on the Hermean magnetosphere will be presented in a later paper.

The size of the simulation box was \( 900 \times 600 \times 600 R_M \)
and it was divided into \( \sim 270,000 \) computational cells. The smallest cell was \( 0.02 R_M \) in each direction, and we used 11 levels of refinement. The inner boundary of the simulation was located at the surface of Mercury. The Mercury simulation was carried out with a version of BATS-R-US which runs on high-end workstations.

Figure 1 shows a three-dimensional rendering of the simulation results. The electric current density is shown in gray scale in the noon-midnight meridian and in a cross sectional plane in the tail. Closed magnetic field lines are shown by dark solid lines, while open magnetic field lines connected to the northern high latitude region are represented by light solid lines. The open-closed magnetic field boundary is marked by a circle.

Inspection of Figure 1 clearly reveals two major current systems in Mercury's magnetosphere: the magnetopause current and the cross tail current. An additional current is also present due to the magnetic field jump across the bow shock. It can be seen that the closed magnetic field lines are
rotated and twisted due to the presence of a $B_y$ component in the IMF. This effect has been observed at Earth [Kaymaz and Siscoe, 1998] and reproduced by global MHD simulations of the terrestrial magnetosphere [Gombosi et al., 1999].

The interplanetary magnetic field vector is in the equatorial plane ($B_z = 0$) and it points 20 degrees from the radial direction. The $B_y$ component is from dawn to dusk. Due to the presence of a $B_y$ component the closed magnetic field lines are pushed down on the dawn side and pushed up on the dusk side. A similar twist can be also observed for the open magnetic field lines. In addition, the axis of the magnetotail is also shifted duskward. The twist and rotation of the magnetotail can be well observed in the equatorial and non-midnight cuts shown in Figure 2.

Figure 2 shows the equatorial (left panel) and noon-midnight meridian (right panel) cuts of the simulated Hermean current system. The IMF vector is in the equatorial plane.

The cross-tail and magnetopause currents clearly form a unified current system and the cross tail current closes through the magnetopause current. It is interesting to note that on the dawn side the near terminator magnetopause and the quasi-parallel segment of the planetary bow shock are closely pushed together, while they are clearly separated on the dusk side.

In the equatorial plane the current is strongest in a relatively narrow region on the dawn side. This is the region where the field lines strongly bend as they enter the magnetotail. It should be noted that due to the presence of a significant $B_y$ component the cross tail current sheet is twisted into an S shape and rotated. The strong current density on the dawn side is the region where the strong cross tail current is close to the equatorial plane.

The right panel of Figure 2 shows the noon-midnight cross section of the current system. The cross-tail current intersects this plane just below the equatorial plane. This is another manifestation of the twist and rotation of the cross-tail current. It is interesting to note that in this plane the magnetopause current is stronger on the northern side. This is also due to the distortion of the tail configuration.

Overall, our simulation indicates that Mercury has a highly compressed magnetosphere which is dominated by the global magnetopause-tail current system. Peculiar features include very large areas of the open field lines on the surface of Mercury, very small size of the magnetosphere compared to the size of planet itself and a nearly merged quasi-parallel shock and magnetopause on the dawn side.

4. SATURN

Saturn's magnetosphere is quite complex due to the influence and interaction of the solar wind, the planetary rotation and the plasma sources, each of which is in some way drastically different from Earth. The solar wind, for example, has quite different characteristics at Saturn than at Earth. The density is much lower, the magnetic field magnitude is smaller, and the nominal Parker spiral gives a magnetic field that is almost completely azimuthal ($\theta = 85^\circ$). All these factors combine to determine the overall size and configuration of the magnetosphere. In addition, Saturn's rotation modifies the structure of the inner magnetosphere. Saturn's large radius and short rotation period produce enough torque on the plasma of the inner magnetosphere to cause it to corotate with the planet. Finally, the Kronian system has several neutral gas sources. These include Saturn, the rings, the icy satellites, Titan's neutral gas torus and Titan itself. The neutrals from these sources are ionized by various processes including charge exchange and photoionization and lead to a significant source of plasma in the inner magnetosphere.
In order to model the important physical processes while at the same time limiting the complexity of our calculation, several simplifications have been made. First, we assume that the planetary magnetic field is a pure dipole aligned with the rotation axis. For Saturn this is a very good approximation. Second, we approximate the plasma sources in the Saturnian system by neglecting the sources and sinks associated with Saturn itself but include sources corresponding to the rings, icy satellites and the neutral gas torus associated with Titan (but not Titan itself). In a later publication the neglected sources will be taken into account. The MHD source terms associated with the mass loading effects are given by Gombosi et al. [1996] and Combi et al. [1998].

The neutral cloud that results from Titan’s presence in the magnetosphere is modeled as an axially symmetric torus centered around the orbit of Titan. The torus is taken to be filled with neutral particles of mass \( m_n = 14 \text{ amu} \). The model takes into account the effects of photoionization, electron impact ionization and charge transfer. Details about the neutral gas distribution in the Titan torus and the associated plasma source terms are given by Barbosa [1987] and Ip [1992]. The total mass loading rate from the Titan torus is assumed to be \( \sim 2.3 \times 10^{20} \text{ s}^{-1} \) with a peak production rate of \( \sim 0.3 \times 10^{23} \text{ cm}^{-3}\text{s}^{-1} \) at Titan’s orbit (20.3 \( R_S \)).

The plasma source associated with the icy satellites and rings were taken from Ip [1997] and Richardson [1998]. These rates refer to the equatorial plane of Saturn. We assumed that outside the equatorial plane the source decreases as \( \exp(-z^2/H^2) \), where the scale height, \( H \) is 0.35 \( R_S \). The total mass loading rate from the rings and icy satellites is assumed to be \( \sim 1.5 \times 10^{27} \text{ s}^{-1} \) with a peak production rate of \( \sim 160 \times 10^{-6} \text{ cm}^{-3}\text{s}^{-1} \) at 4.6 \( R_S \).

The solar wind parameters used in the simulation are the following: heliocentric distance 9.54 AU, \( n_e = 0.1 \text{ cm}^{-3} \), \( u_e = 400 \text{ km/s} \), \( T_e = 1.8 \times 10^5 \text{ K} \), \( a = 50 \text{ km} \text{s}^{-1} \), and \( B = 0.5 \text{ nT} \). At Saturn’s orbit the IMF is assumed to be in the y direction (Parker spiral) pointing from dawn to dusk. These parameters correspond to an ion-acoustic Mach number of 8 and an Alfvénic Mach number of 3.9. The specific heat ratio is 5/3.

The planetary parameters were taken to be the following: radius \( R_S = 60,268 \text{ km} \), angular velocity \( \Omega = 1.66 \times 10^{-4} \text{ s}^{-1} \), equatorial magnetic field \( B_e = 0.208 \text{ G} \), the dipole is non-tilted and oppositely oriented than the terrestrial dipole.

The outer boundaries of the simulation domain are located at 192 \( R_S \) upstream and 588 \( R_S \) downstream. The other boundaries are located at 192 \( R_S \). This large computational domain ensures that the influence of the boundaries on the solution is negligible. The boundary conditions applied at the outer boundaries are those of the free streaming solar wind. The inner boundary associated with Saturn is applied at 3 \( R_S \). At this radius the density and pressure are allowed to float and the magnetic field is taken to be only the intrinsic planetary dipole. The velocities are fixed to coincide with the rotation of Saturn. The simulation involved about \( 10^6 \) computational cells. The smallest cell was \( \sim 0.19 R_S \) in each direction, and we used 8 levels of refinement.

Figure 3 is a 3D representation of the solution. The grayscale represents the mass density in the equatorial and noon-midnight meridian planes. The Figure also shows the computational grid in these two planes, indicating the refinement near the planet. White lines represent plasma flow lines in the inner magnetosphere.

It can be seen in Figure 3 that a bow shock forms upstream of the planet. The subsolar distance of the shock is about 30 \( R_S \). The magnetopause separates the shocked solar wind from the region dominated by the planetary magnetic field. The subsolar point of the magnetopause is located at around 20 \( R_S \). Since the Titan torus is centered around 20 \( R_S \), a significant plasma source is located in the magnetosheath between the shock and the dayside magnetopause. This plasma source results in additional deceleration and heating of the shocked plasma flow, thus compressing the Kronian magnetosphere.

Inspection of Figure 3 reveals that the plasma density is highest near the equatorial plane. This is due to the combined effect of rapid rotation and the concentration of plasma sources near the equatorial plane. Near the equatorial plane the plasma within Titan’s orbit rotates with the planet. Beyond Titan’s orbit the corotation breaks down due to mass loading and weakening magnetic field. In this region the plasma exhibits a complicated convection pattern as can be seen by examining the convection streamlines in Figure 3.

The plasma convection pattern in the equatorial plane is shown in the left panel of Figure 4. The panel also shows the plasma mass density distribution (grayscale coded). It can be seen that the plasma density is significantly enhanced in the innermost region (within about 10 \( R_S \)), where mass loading from the rings and icy satellites plays a major effect. The density has a minimum between about 10 and 15 \( R_S \) where there is no major plasma source. This minimum extends to Titan’s orbit at around 1400 LT. This density minimum is formed because the magnetopause is near Titan’s orbit in this region and the incoming mass loaded plasma is diverted into the magnetosheath (outside the magnetopause) or diverted towards the tail through high latitudes (inside the magnetopause).

At around 2000 LT a density maximum is formed near Titan’s orbit. This maximum is a consequence of the interplay between solar wind driven convection and corotation: the two effects nearly cancel and the plasma nearly stagnates. The low plasma velocity naturally leads to high densities.
Tailward from about $x = -20 R_E$, the effects of corotation become increasingly negligible and solar wind driven magnetospheric convection starts to dominate. We note that a magnetic X-line is formed at around this distance (not shown in the Figures).

The right panel in Figure 4 shows the grayscale coded electric current density in the noon-midnight meridian. One of the most prominent features seen in this panel is a thin equatorial current ring extending from about $4 R_E$ to approximately $12 R_E$. This current ring is formed by the pickup current associated to the inner plasma source due to the rings and icy satellites. The plasma source peaks at around $5 R_E$. At this distance the current is diverted from the current disc and connects to the high-latitude ionosphere along magnetic field lines.

Another current system seen in Figure 4 is associated with mass loading in the Titan torus. This current system connects to the high-latitude ionosphere poleward from the icy satellite/ring current system. It is interesting to note that on the nightside the Titan torus current system extends towards the magnetotail and connects to the cross-tail current. On the dayside the Titan torus current is split into two parts: one is connected to the source inside the magnetopause, while the second one connects to the torus source outside the magnetopause. The two parts of the current system are separated by a gap. The Titan torus current system is also a pickup generated current.

5. SUMMARY

We presented global MHD simulations of the interaction of the solar wind with two very different magnetized planets, Mercury and Saturn. The simulations were carried out with BATS-R-US, a newly developed high performance adaptive MHD code. Similarities in planetary magnetospheres, in spite of differences in ionospheric conductances, configurations, plasma and energy sources and sinks, can help us to understand better the full range of phenomena and processes in the Earth’s magnetosphere. Planetary magnetospheres help us to extend observed magnetospheric phenomena into different parameter regimes.

Both simulations considered the interaction of the “nominal” solar wind (with Parker spiral IMF) with the two planets. Mercury was assumed to be a non-conductive body with negligible plasma sources in the Hermean environment. On the other hand Saturn was assumed to have two major
plasma source regions: one associated with the rings and icy satellites and the other with the neutral torus around Titan’s orbit.

In the case of Mercury the intrinsic magnetic field is very weak, so that most of the field lines emanating from the surface of the planet are connected to the IMF either upstream or downstream. Closed field lines appear only at latitudes less than 50°. The whole magnetosphere is twisted and rotated due to the presence of a significant dawn to dusk $B_y$ component of the IMF. The simulation clearly shows the formation of a delicately connected current system consisting of the tail and magnetopause currents.

In the case of Saturn a very interesting and complicated configuration arises from the interplay between mass loading, rapid planetary rotation and solar wind driven convection. In the equatorial plane corotation was obtained within Titan’s orbit, while outside Titan’s orbit solar wind driven convection dominates the plasma motion. Mass loading generates two current systems which connect the ring/icy satellite current disk and the Titan torus to the high-latitude ionosphere of Saturn.

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