Magnetic portraits of Tethys and Rhea

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Abstract

The Cassini spacecraft made a single flyby each of Saturn’s icy moons Tethys and Rhea in late 2005. The magnetic field observations from these flybys provide unique portraits of the magnetic properties of these moons. These are the first observations of interactions of these inert moons with the sub-magnetosonic plasma of Saturn’s magnetosphere. Because the upstream field and plasma conditions are extremely stable, we are able to observe the interaction in great detail. One of the major findings of this study is that the region of plasma depletion is greatly elongated along the field direction in a sub-magnetosonic interaction. Based on the consideration of field aligned velocities of thermal ions, we show that overlapping particle shadow wings form downstream of an inert moon such that in each of the particle shadow wings, particles of specific field aligned velocities are depleted. Other major findings of this study are: (1) Tethys and Rhea are devoid of any internal magnetic field; (2) No induction generated field was observed, as expected because of the extremely weak primary inducing (time varying) field; (3) There is no appreciable mass-loading of Saturn’s magnetosphere from Tethys and Rhea; (4) We predict that wave particles interactions would be generated that smooth out the phase space holes created by the moon/plasma interaction. These waves serve to isotropize the plasma distribution function.

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1. Introduction

A campaign to closely observe four of the largest icy satellites of Saturn (Enceladus, Tethys, Dione and Rhea) was implemented by the Cassini science teams during the year 2005. In this campaign, three close flybys of Enceladus and one each of Tethys, Dione and Rhea were made to study their geology and atmospheres from remote sensing and to understand their interactions with the saturnian magnetosphere. The results from Enceladus have already been presented in a special issue of the journal “Science” and showed that Enceladus is currently geologically active and vents 150–350 kg/s of neutral material (mostly water) into its external environment from a plume located near its south pole (Hansen et al., 2006; Waite et al., 2006) which mass-loads the corotating plasma (Dougherty et al., 2006). The magnetic field data from Dione indicate that this moon also mass-loads the plasma (though very feebly compared to Enceladus) and therefore this moon is in the same class of interaction as Enceladus. The results from Dione will be presented elsewhere. In this work we present first magnetic field observations from Tethys and Rhea which we show below are inert objects and absorb most of the plasma incident on them.

2. The physical characteristics of Tethys and Rhea

Tethys is the fifth largest satellite of Saturn with a mean radius of 533 km and a mean density of 0.9735 g/cm³. The extremely low density and an ellipsoidal shape close to that expected of a homogeneous body (Thomas et al., 2006) suggest that Tethys is an undifferentiated body consisting primarily of water ice. The highly cratered surface does not provide any hint of current geological history and therefore, unlike Enceladus, no vents or vent associated atmosphere are expected on this body.
Table 1
The physical properties of Saturn's large inner icy satellites and their environment

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Enceladus</th>
<th>Tethys</th>
<th>Dione</th>
<th>Rhea</th>
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<td>Radius (km)</td>
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<td>533.0&lt;sup&gt;a&lt;/sup&gt;</td>
<td>561.6&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>Density (g/cm&lt;sup&gt;3&lt;/sup&gt;)</td>
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<td>0.974&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.5&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>T&lt;sub&gt;bounce&lt;/sub&gt; electrons (s) (90° eq.), thermal, 1, 10, 100 keV</td>
<td>11, 19, 0.6, 0.2</td>
<td>10, 2.3, 0.72, 0.23</td>
<td>9.8, 2.93, 0.93, 0.29</td>
<td>12.9, 4.1, 1.3, 0.41</td>
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<td>T&lt;sub&gt;bounce&lt;/sub&gt; ions (s) (90° eq.), thermal, 1, 10, 100 keV</td>
<td>375, 38, 12, 4.3</td>
<td>328, 47, 15, 5.3</td>
<td>243, 60, 19, 6.8</td>
<td>263, 83, 27, 9.5</td>
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<td>Drift vel ions (km/s), thermal, 1, 10, 100 keV</td>
<td>0.001, 0.03, 0.30, 3.0</td>
<td>0.003, 0.06, 0.61, 6.1</td>
<td>0.01, 0.1, 1.1, 10.6</td>
<td>0.02, 0.23, 2.3, 22.8</td>
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<td>Drift vel electrons (km/s), thermal, 1, 10, 100 keV</td>
<td>−0.0003, −0.03, −0.3, −3</td>
<td>−0.001, −0.06, −0.61, −6.1</td>
<td>−0.001, −0.1, −1.1, −10.6</td>
<td>−0.02, −0.23, −2.3, −22.8</td>
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<td>T&lt;sub&gt;contact&lt;/sub&gt; ions (s), thermal, 1, 10, 100 keV</td>
<td>19.4, 19.4, 19.2, 17.4</td>
<td>31.4, 31.3, 30.8, 26.6</td>
<td>28.1, 28.0, 27.3, 22.2</td>
<td>26.8, 26.7, 25.8, 19.2</td>
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<tr>
<td>T&lt;sub&gt;contact&lt;/sub&gt; electrons (s), thermal, 1, 10, 100 keV</td>
<td>19.4, 19.4, 19.6, 21.9</td>
<td>31.4, 31.4, 31.9, 38.2</td>
<td>28.1, 28.6, 28.9, 38.2</td>
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<td>E&lt;sub&gt;crit&lt;/sub&gt; electrons (keV)</td>
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<td>2.48</td>
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<td>4.1</td>
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<sup>Note</sup>. The bounce period has been calculated for particles that mirror near the magnetic equator. Particles that have field-aligned velocity near the equator would have bounce periods which are a factor of 1.8 longer.

<sup>a</sup> Jacobson et al. (2006).
<sup>b</sup> Calculated by Khurana et al. (2007), this manuscript.
<sup>c</sup> Sittler et al. (2006).
<sup>d</sup> Jurac and Richardson (2005).

Rhea is the second largest satellite of Saturn with a mean radius of 764 km. Its mean density is 1.233 g/cm<sup>3</sup> and its normalized moment of inertia <i>C</i>/<i>M</i><sup>−2</sup><i>R</i><sup>2</sup> is 0.391 close to 0.4 expected of an undifferentiated body (Anderson and Schubert, 2007). Its shape is also close to that expected of a homogeneous body (Thomas et al., 2006). Modeling of its interior by Anderson and Schubert (2007) shows that Rhea is a homogeneous mix of ice (75%) and rock (25%) with some compression of ice and a phase change of ice I to ice II at depth. The geology of Rhea and its cratering history suggests that it may have been active in the first 0.5 byr of its history but has remained inactive since (Plescia, 1985) and is also not expected to possess active vents or an appreciable atmosphere today. Moore and Schenk (2007) have recently produced a digital elevation model for a portion of Rhea’s surface. They suggest that the absence of any regions that would qualify as plains enforces the perception that Rhea shows no record of cryovolcanic resurfacing. The surface temperature of this moon ranges from 53 to 99 K.

3. The field and plasma conditions at the orbits of Tethys and Rhea

Tethys and Rhea orbit in the inner magnetosphere of Saturn. The thermal plasma in Saturn’s magnetosphere is effectively corotating with Saturn and has much higher speed than the Keplerian speeds of these moons (see Table 1). The plasma therefore continually overtakes these moons and bombards their surfaces such that the lagging sides receive the highest flux doses. Much of our knowledge about the field and plasma environment in the vicinity of these moons came from the Voyager 1 and 2 spacecraft which flew through the magnetosphere in 1980 and 1981 (Acuña et al., 1983; Lazarus and McNutt, 1983). One distinguishing characteristic of Saturn’s magnetosphere is that the neutrals are many times more abundant than the charged species (Jurac et al., 2002). Jurac and Richardson (2005) show that the densities of H<sub>2</sub>O neutrals dominate near the orbit of Enceladus but OH molecule dominates elsewhere. They also
Magnetic portraits of Tethys and Rhea

show that the molecular cloud which has its peak density near the orbit of Enceladus is the main source for plasma in Saturn’s magnetosphere.

In the inner magnetosphere of Saturn, charged particles carry out gyro and bounce motions on the nearly dipolar field lines of Saturn. The gyroradii of most electrons and ions near the icy moons are much smaller than the radii of the moons (see Table 1). So, the effective absorption cross-sections of the moons are just slightly larger than the sizes of the moons. Because of the lower mass of electrons, their bounce periods (Table 1) are much shorter than those of ions with the same energy. The energetic electrons and ions do not travel at the corotation speed of thermal or cold plasma because they are subject to additional drifts in the azimuthal direction from the gradient and curvature of the magnetic field. Ions drift in the direction of the corotating flow and therefore move faster than the corotating cold plasma. Electrons drift in the opposite direction and therefore move slower than the corotation flow. This effect increases the contact time of the electrons with the moons and therefore energetic electrons tend to show very well-developed plasma depletions along the field direction and in the direction of electron wakes near the icy moons. These broad depletions have been given the name micro-signatures. Electrons with an energy of $E = E_{\text{crit}}$ have their drift velocity equal but opposite in sign to that of the corotational flow in the moon’s rest reference. Electrons with energies higher then $E_{\text{crit}}$ approach the moon from the leading side and form a wake on the trailing side (see Paranic et al., 2005).

4. Coordinate system and trajectories

Throughout this work, we shall use a coordinate system called the “satellite interaction system” whose $x$-axis points along the corotation direction of the plasma, whose $y$-axis points toward Saturn and the $z$-axis lies along the spin pole of Saturn. The right-handed coordinate system is centered at the moon’s center and the distances are measured in terms of moon radii ($R_M$). This coordinate system readily describes the interactions of the moons with the plasma because the magnetic field lies essentially along the $z$-axis and the wakes are aligned along the $x$-axis. Fig. 1 shows the trajectories of Cassini past Tethys and Rhea in three different orthogonal planes of this coordinate system. It can be seen that Cassini remained downstream of Tethys and Rhea during the flybys.

5. Super-magnetosonic interaction of an inert moon

A great deal of our understanding of an inert moon’s interaction with a flowing plasma has resulted from the Apollo era studies of the interactions of the Earth’s Moon with the solar wind (Whang, 1968a, 1968b; Wolf, 1968; Siscoe et al., 1969). A good review of the observations and modeling results from this period is provided by Schubert and Lichtenstein (1974). More recent interest on the topic resulted from the need to understand the space environment of artificial satellites such as the Explorers and the Space Shuttle (Samir et al., 1983). Observations of the lunar wake with modern field and plasma instru-
ments became available more recently with the lunar swing-by of the Wind spacecraft (Owen et al., 1996; Ogilvie et al., 1996; Bosqued et al., 1996), and the near-surface observations from the Lunar Prospector (Halekas et al., 2005). These studies reveal that the Moon is non-conducting, lacks a global magnetic field and creates little or no plasma pick-up in its vicinity. In this interaction, the plasma that is incident on the Moon is neither slowed down nor diverted around the Moon and therefore simply slams into it and gets absorbed. The magnetic field on the other hand simply passes through the Moon because of the poor conductivity of its outer layers. Observations and modeling show that the Moon’s interaction with the solar wind can be essentially described in terms of a fluid approach though many kinetic aspects such as charge separation and ion heating cannot be ignored. Near the icy moons of Saturn, the magnetic field is almost perpendicular to the flow direction. We will therefore restrict our discussion of the Moon’s interaction with the solar wind to the case where $V_\perp B$.

As the solar wind is super-magnetosonic ($v_0/v_{ms} > 1$, where $v_0$ is the plasma flow velocity and $v_{ms}$ is the plasma fast mode speed), its ion plasma distribution is akin to that of a cold beam moving with the bulk velocity of the solar wind (see Fig. 2). In such a distribution, there are very few ions which have substantial velocities in the direction parallel to the magnetic field. Therefore when a magnetic flux tube interacts with the Moon, the charged particles within it that were initially located above or below the Moon do not have sufficient time to precipitate on to the surface. As a result, just downstream of the Moon, the extent of the ion wake along the field direction is roughly the same as the size of the Moon. In the flow direction, an extended wake forms behind the Moon which is always devoid of plasma close to the Moon (in a region called the void region) but starts filling up with distance as the plasma streams towards the wake center along the field lines (see Fig. 3). Electrons, being more mobile, race ahead of the ions causing a negative potential in the central wake [$\sim -400$ V at the center of the Moon’s plasma wake, with electric fields of the order of $2 \times 10^{-4}$ V/m (Ogilvie et al., 1996)]. The bi-directional streaming of ions and electrons along the field is responsible for ion energization and many wave/particle interaction effects (Samir et al., 1983; Travincek et al., 2005). In addition, in the direction perpendicular to the magnetic field and the flow ($Y$ direction in Fig. 3b), field lines are drawn in towards the wake center because of the reduction in plasma pressure behind the Moon and the need for the total pressure (particle + magnetic) to balance in an MHD fluid. The resulting enhancement of $|B|$ inside the cavity is maintained by diamagnetic currents flowing on the surface of the plasma cavity (Colburn et al., 1967; Owen et al., 1996). The Mach cone that defines the boundary of the void region for this situation is given by $\tan^{-1}(V_s/V_\text{flow})$ where $V_s$ is the sonic speed of the plasma (see Fig. 3a). The reason that the sonic speed (rather than Alfvén or magnetosonic speed) of the plasma essentially determines this Mach cone angle is that the interaction is a slow mode transition across which the field increases (decreases) on one side and the plasma density decreases (increases) on the other. Outside the plasma shadow zone, a fast mode (also known as the magnetosonic mode) rarefaction wave front propagates (Siscoe et al., 1969) across which the magnetic field strength and plasma density vary in phase (i.e., both decrease on the wake side). Because the magnetosonic wave velocity is anisotropic with respect to the field direction, the rarefaction wave Mach cone is also expected to be anisotropic. Recently, Halekas et al. (2005) using observations from the Lunar Prospector showed that the rarefaction front is indeed defined by the magnetosonic Mach cone. However, because the orbit of Lunar Prospector lies very close to

![Fig. 2. Distribution function of a supersonic plasma in the 2-D velocity space (left) and in two cuts along the perpendicular (top right) and parallel (bottom right) directions to the magnetic field.](image)

![Fig. 3. The interaction of an inert moon with a super-magnetosonic plasma. (a) The interaction in a plane containing the flow and magnetic field directions and (b) view of the perturbed field lines in the wake in a plane normal to the direction of the flow. Just behind the moon, the ion wake has a radius roughly equal to that of the moon and begins to fill further downstream.](image)
the Moon, rotational asymmetries caused by the wave velocity anisotropies are hard to detect in the data.

6. The Tethys and Rhea encounters

Cassini flew through the wake of Tethys on September 24, 2005 at a close approach distance of 3.83 $R_T$. Near the closest approach, the spacecraft was downstream of Tethys and located substantially south of the cold plasma wake (see Fig. 1). From the analogy of lunar wake formation, the spacecraft at this distance would be expected to pass through the rarefaction front where both field and plasma pressures drop in value from their background value. Fig. 4 shows a 25-min segment of the magnetic field data obtained during the flyby. A clear bipolar perturbation in the $B_y$ component is seen. In order to show the perturbations more clearly, in Fig. 5 we detrend all three of the field components and the field magnitude with a running average of 600 s. Surprisingly, the field magnitude (lowest panel in Fig. 5) is seen to strengthen (rather than weaken as expected of a rarefaction region) near the closest approach. In addition, the perturbations in the $Y$ component are consistent with a picture where the field lines have been drawn in towards the $Y = 0$ plane even at this large $Z$ distance from the wake center. In the next section, we will show that the extended interaction region of Tethys results from the subsonic nature of the interacting plasma.

The observations of Figs. 4 and 5 also show strong wave activity with a period of $\sim 8$ s in the data. The wave amplitude did not increase as the spacecraft approached the moon. A spectral analysis of the data shows that the waves are field-guided and are left-handed circularly polarized. These waves are ion-cyclotron waves observed regularly in the E-ring region (4–8 $R_S$). Their origin lies in the neutral cloud which is continually replenished by Enceladus and eroded by the charged particles of Saturn’s magnetosphere (Leisner et al., 2006).

The Rhea encounter took place on November 26, 2005 when the spacecraft was inbound to Saturn. Cassini flew through the central cold plasma wake at a radial distance of 1.67 $R_H$ (see Fig. 1 for trajectory). Fig. 6 shows the observations from this flyby. A very clear field enhancement in the field strength is seen near the closest approach. In order to understand the small perturbations in the field components, we plot the detrended data in Fig. 7 where we have subtracted running averages of 10-min duration from all three components and the field magnitude. Similar to the Tethys signature, a bipolar perturbation is seen in the $B_y$ component. The sign of this bipolar perturbation is consistent with a picture where field lines have been drawn into the wake from the flanks (see Fig. 3, right) to balance the particle pressure deficit caused by the plasma absorption.

7. Sub-magnetosonic interaction of an inert moon

The main difference between the solar wind and the plasma in the saturnian magnetosphere is the transonic ($v_0/v_s \sim 1$, where $v_s$ is the speed of sound in plasma) but sub-magnetosonic ($v_0/v_{ms} < 1$) nature of the flow in Saturn’s magnetosphere (see Table 1). In a subsonic or transonic plasma, there are many particles which have field-aligned speeds comparable to or faster than the flow speed (see Fig. 8). Thus while the magnetic flux tubes are in contact with the moon, not only those particles which were directly ahead of the moon, but even those fast moving particles which were above or below the moon earlier can precipitate on to the moon. Fig. 9 depicts the interaction of ions and electrons of different field
aligned velocities. First of all, let us look at energetic electrons with energies $E > E_{\text{crit}}$, i.e., electrons which drift in opposite sense to the corotation flow (see Table 1). These electrons have extremely short bounce periods (see last row of Table 1). Because for these electrons $T_{\text{bounce}} \ll T_{\text{contact}}$, the whole flux tube extending from the northern ionosphere of Saturn to its southern ionospheres is emptied out. As a result, a large micro-signature is formed upstream of the moon along its trailing side (in the sense of the moon’s Keplerian motion). Paranicas et al. (2005) have reported such micro-signatures upstream of Enceladus and Tethys for electrons with energies in the MeV range. Because the diffusion time scales in the inner magnetosphere are long, the micro-signatures are seen to persist over long distances upstream ($>29^\circ$ of saturnian longitude) (Paranicas et al., 2005). In Fig. 9, we depict the upstream shadow of extremely energetic electrons by the cyan
Magnetic portraits of Tethys and Rhea

Fig. 7. Magnetic field perturbations from the Rhea flyby. The perturbation vectors were obtained by subtracting a running average background of 10-min duration from the observations of Fig. 6. The locations of expansion fans which bring field and plasma into the wake are marked.

Fig. 8. Ion distribution function for a sub-magnetosonic plasma. In such a plasma many ions have field-aligned velocities comparable to the plasma flow velocity. Such fast ions can get absorbed by the moon even if their distance from the moon along the field line was large when the flux tube was upstream of the moon.

In order to understand the interaction of a representative ion let us follow its trajectory as it moves up against the field line at a velocity $-v_\parallel$ while being carried downstream at the flow speed, $v_0$. If this particle is located anywhere in the upstream orange cylinder drawn in the lower half of the figure and defined by

$$ (X \cos(\theta) + Z \sin(\theta))^2 + Y^2 = R_M^2, $$

$$ \theta = \tan^{-1}(-v_\parallel/v_0), $$

it is doomed to precipitate on the surface of the moon. Here $R_M$ is the radius of the moon. In Fig. 9a, we show the shadow formed by these particles by a dull orange cylinder drawn downstream of the moon in the upper half of the figure. Because of its similarity in appearance to a structure called the Alfvén wing, we use the term particle shadow wing to denote this cylindrical shadow form.

Now let us look at a particle moving down in the direction of the field line at a velocity $v_\parallel$. It would precipitate on to the moon if it is located in the cylinder defined by

$$ (X \cos(\theta) - Z \sin(\theta))^2 + Y^2 = R_M^2. $$

The particles in adjacent flux tubes (to the left or to the right of these flux tubes) and having the same parallel velocity as the doomed particles avoid absorption, a process which has been termed “leapfrogging” by Paonessa and Cheng (1985).

Ions which have field-aligned velocities greater than the particles of orange cylinder would form particle shadow wings inclined at higher angles than the yellow shadow wing. Similarly particles with smaller field-aligned velocities (green and blue cylinders) would form shadow wings with lower inclinations. Fig. 9b shows the cross-sections of several particle shadow wings in a $Y-Z$ plane drawn at a downstream distance.

Cold plasma and those thermal particles which have a pitch angle of $\sim 90^\circ$ and were earlier directly upstream of the moon strike the moon and are absorbed. A long wake depleted of these particles forms behind the moon (dark gray horizontal cylinder in Fig. 9a and a dark gray circle in Fig. 9b) in a process extremely analogous to the supersonic interaction of the solar curtain.

The locations of expansion fans which bring field and plasma into the wake are marked.

Fig. 7.

Fig. 8.
wind with an inert moon. The Rhea central wake is an example of this cold plasma wake.

With this understanding of the subsonic plasma interaction, it is easy to see why the magnetic field enhancement signature for Tethys is so elongated in the direction of the background field. Because, the energetic particles are lost not only in the cold plasma wake but also all along the field line that came into contact with the moon, the particle pressure is depressed over a large region along the flux tubes. The field lines are therefore drawn into the elongated “wake” (see Fig. 9b, dotted lines) from the flanks of the interaction region to compensate for the plasma pressure deficit. An interesting consequence of the field-aligned elongation of the interaction region is that the expansion fan is no longer able to reach the central wake along the field lines. However, an expansion wave still propagates from the flanks of the interaction region and brings field and plasma into the wake region (Fig. 9b). In Figs. 5 and 7 which show the detrended data from the Tethys and Rhea encounters, respectively, clear field depressions are seen outside of the regions of field enhancements. These are the expansion fan regions of these sub-magnetosonic interactions.

8. Summary and discussion

Sub-magnetosonic and super-magnetosonic plasma interactions with inert moons share many similarities. In both cases, a long wake devoid of plasma is formed downstream of the moon which is eventually filled by plasma drawn into the wake region by expansion fans. The field strength is strengthened in the central wake but is depressed in the expansion fan region surrounding the central wake. However, there are many differences in the two types of interactions. The main key difference is in the extent of the ion depleted wake in the field-aligned direction. For a super-magnetosonic interaction, just behind the moon, the ion absorption wake radius is nearly identical to that of the moon while in a sub-magnetosonic interaction, the wake is elongated appreciably in the direction of the magnetic field. Another key difference that distinguishes the two interactions is that in a sub-magnetosonic flow the expansion fan in the field-aligned direction recedes to large distances from the moon whereas it begins at the boundary of the moon in a super-magnetosonic interaction.

We would also like to remark about the absence of any internal field possessed by these moons. The closest approach distance for Tethys was 3.83 $R_T$ and for Rhea it was 1.67 $R_{RH}$. We believe that in both of these data sets, any dipolar field at a level of 1 nT would have been easily detectable. This puts an upper bound of 56 nT for the surface field strength for any internal field from Tethys and 5 nT for Rhea. We also did not detect any measurable induction field from these moons. This is expected because in Saturn’s magnetosphere, because of the axisymmetric nature of Saturn’s field, there is no strong driving signal at the rotation period of Saturn. As a global conductor induces a dipolar response from a time-varying uniform field, induction studies from flyby data are inadequate to infer the extremely weak dipolar response that would be generated by a global conductor such as a subsurface ocean.

Our observations of the magnetic field interactions also rule out any appreciable mass-loading of Saturn’s magnetosphere by Tethys and Rhea. In contrast, near Enceladus, modeling studies...
of the plasma sputtering environment and the magnetic field signatures show that between 1.5 and 3 kg/s of the neutral material (mostly water molecules) is picked-up by the magnetosphere of Saturn in the immediate vicinity of Enceladus (Burger et al., 2007; Khurana et al., 2007). The rest of the neutral gas and dust spread around the orbit of Enceladus to ultimately form the neutral cloud and the E ring of Saturn. Fig. 10 compares the plasma interaction of a mass-loading (or a highly conducting) moon with that of a mass-absorbing moon in a downstream plane normal to the background flow. When a moon mass-loads the flow, the field lines bulge out to avoid the plasma slow-down region (Fig. 10, left). If the wake is filled with newly picked-up plasma from the moon’s vicinity, the bulge persists into the wake and a field minimum is observed at the center of the wake (for example, in Io’s wake). However, for an inert moon, the field lines are drawn into the wake to compensate for the reduction of plasma pressure there, enhancing the local field strength (Fig. 10, right). Fig. 10 shows that the expected signatures for the $B_y$ component are exactly opposite in sign to each other for the two situations. Our observations of $B_y$ are consistent with an inert interaction and rule out any appreciable mass-loading. Our data therefore show that sputtering generated atmospheres. For Rhea, Saur and Strobel estimated that it had the potential to hold a thin atmosphere with a column density approaching $6 \times 10^{17}$ particles/m$^2$. They further estimated that the height-integrated Pedersen conductivity in the ionosphere of Rhea would be $\sim 30$ S, much greater than the local Alfvén conductance of $\sim 7.6$ S. Such a large conductivity would result in a strong field line draping type Alfvénic interaction producing a $\delta b/B_0$ of 30%. Our observations rule out such an interaction and are at variance with their modeling results for Rhea.

Finally, we would like to remark on the possibility of strong wave–particle interactions in the wakes of inert moons. The moon/plasma interaction described in Fig. 9 creates phase space holes over a large range of velocities and distances. Electrostatic and electromagnetic waves would be expected to be generated that smooth out these phase space holes and isotropize the plasma distribution function once again.

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