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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.

Keywords: Saturn, satellites; Satellites, surfaces; Saturn, magnetosphere; Enceladus

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/cm^3. 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.

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Table 1
The physical properties of Saturn's large inner icy satellites and their environment

Satellite	Enceladus	Tethys	Dione	Rhea
Radius (km)	252.1[a]	533.0[a]	561.6[a]	764.4[a]
Density (g/cm^3)	1.61[a]	0.974[a]	1.5[a]	1.23[a]
Radial distance (R_s)	3.95[a]	4.89[a]	6.26[a]	8.74[a]
$\|\mathbf{B}\|$ (nT)	370[b]	167[b]	75[b]	25[b]
v (relative, km/s)	26[b]	34[b]	40[b]	57[b]
n_e (cm^{-3})	40[c]	30[c]	13[c]	2[c]
m_i (AMU)	18[d]	17[d]	17[d]	17[d]
T_e (eV)	10[c]	20[c]	60[c]	100[c]
T_i heavy ions (eV)	30[c]	50[c]	90[c]	100[c]
V_A (km/s)	301	161	110	93
C_s (km/s)	19	26	37	43
β	0.005	0.03	0.14	0.26
M_A	0.09	0.21	0.36	0.61
M_s	1.4	1.3	1.1	1.3
M_{ms}	0.09	0.21	0.34	0.56
f_{ci} thermal ions (Hz)	0.31	0.15	0.066	0.022
f_{ce} thermal electrons (kHz)	10.36	4.68	2.1	0.7
R_g thermal ions (km)	9	25	75	237
R_g thermal electrons (m)	29	90	346	1340
T_{bounce} ions (h) (90° eq.), thermal, 1, 10, 100 keV	11, 1.9, 0.6, 0.2	10, 2.3, 0.72, 0.23	9.8, 2.93, 0.93, 0.29	12.9, 4.1, 1.3, 0.41
T_{bounce} electrons (s) (90° eq.), thermal, 1, 10, 100 keV	375, 38, 12, 4.3	328, 47, 15, 5.3	243, 60, 19, 6.8	263, 83, 27, 9.5
Drift vel ions (km/s), thermal, 1, 10, 100 keV	0.001, 0.03, 0.30, 3.0	0.003, 0.06, 0.61, 6.1	0.01, 0.1, 1.1, 10.6	0.02, 0.23, 2.3, 22.8
Drift vel electrons (km/s), thermal, 1, 10, 100 keV	−0.0003, −0.03, −0.3, −3	−0.001, −0.06, −0.61, −6.1	−0.007, −0.1, −1.1, −10.6	−0.02, −0.23, −2.3, −22.8
$T_{contact}$ ions (s), thermal, 1, 10, 100 keV	19.4, 19.4, 19.2, 17.4	31.4, 31.3, 30.8, 26.6	28.1, 28.0, 27.3, 22.2	26.8, 26.7, 25.8, 19.2
$T_{contact}$ electrons (s), thermal, 1, 10, 100 keV	19.4, 19.4, 19.6, 21.9	31.4, 31.4, 31.9, 38.2	28.1, 28.6, 28.9, 38.2	26.8, 26.9, 27.9, 44.7
E_{crit} electrons (keV)	1061	953.5	792.6	530
T_{bounce} electrons (s), E_{crit}	2.48	3.1	4.1	6.0

Note. 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.
[a] Jacobson et al. (2006).
[b] Calculated by Khurana et al. (2007), this manuscript.
[c] Sittler et al. (2006).
[d] 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^3 and its normalized moment of inertia C/MR^2 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_2O neutrals dominate near the orbit of Enceladus but OH molecule dominates elsewhere. They also