Plasma wake of Tethys: Hybrid simulations versus Cassini MAG data

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[1] The interaction between Saturn’s fifth largest satellite, Tethys, and the corotating plasma of the inner magnetosphere has been studied with a three-dimensional hybrid simulation. Since Tethys possesses neither an intrinsic magnetic field nor a substantial ionosphere, the moon’s surface is directly exposed to the impinging plasma. This leads to the formation of an extended density cavity in the downstream region, expanding above and below Tethys along the magnetic field lines. The resulting deficit of plasma pressure is compensated by a compression of the field lines at the wakeside. By confronting our simulation results with Cassini magnetometer data from the so far only targeted flyby in 2005, we demonstrate that these key features of Tethys’ plasma interaction are quantitatively reproducible within the framework of the hybrid model. Besides, the simulation results illustrate the importance of ambipolar electric fields for ion dynamics in the wake of Tethys.


1. Introduction

[2] On 24 September 2005, the Cassini spacecraft accomplished its so far only close flyby of Saturn’s fifth largest satellite Tethys. As displayed in Figures 1a–c, the spacecraft passed downstream of the moon and southward of its geometric plasma wake. Based on the analysis of data collected by the magnetometer instrument (MAG), Khurana et al. [2008] found Tethys to be an electromagnetically inert object that possesses neither an intrinsic magnetic field nor a substantial ionosphere. These observations are consistent with the model of Saur and Strobel [2005] who found the gravitation of Tethys to be too weak to maintain a substantial atmosphere. These authors estimated a small value of $10^{-3}$/s for ionospheric pick-up rates at Tethys.

[3] Although during the flyby, Cassini remained clearly southward of Tethys, the MAG instrument detected weak magnetic perturbations that could be ascribed to the presence of the moon. The reason for this is schematically explained in Figure 1d. Plasma absorption at the surface of Tethys gives rise to a density cavity at the wakeside. For this reason, the magnetic field lines are drawn into the wake, thus compensating for the loss of magnetospheric particle pressure. Consequentially, the magnetic field is depressed at the flanks of the interaction region. As demonstrated, e.g., by Kallio [2005], in the case of the terrestrial Moon, these effects can be observed only in the immediate vicinity of the obstacle’s optical shadow. However, due to the submagnetosonic nature of the plasma impinging on Tethys, there are many particles which possess large field-aligned velocities (with respect to the corotational flow speed). Therefore, particles which were initially located above (northward) or below (southward) the moon can be absorbed as well when their flux tube comes into contact with Tethys. This leads to an expansion of the interaction region along the magnetic field lines. The key features of this type of plasma interaction have been discussed in detail by Khurana et al. [2008]. By applying a hybrid code, Roussos et al. [2008] succeeded in reproducing Cassini magnetometer data from a similar wakeside flyby of Saturn’s inert satellite Rhea. However, during the Rhea encounter, Cassini passed directly through the cylindrical cold plasma wake of the moon and did not collect data in the elongated plasma shadow.

[4] Within the framework of this study, we present the first application of a global, self-consistent simulation model to the plasma interaction of Tethys. We do not only focus on the overall features of the plasma interaction, but the results are also compared to Cassini MAG observations in the elongated plasma wake southward of the moon. The letter concludes with some general remarks on the applicability of the hybrid model to the plasma environment of inert moons.

2. Simulation Model and Input Parameters

[5] In this study, a three-dimensional, quasi-neutral hybrid model has been applied to the plasma interaction of Tethys. The hybrid approach treats the electrons as a massless, charge-neutralizing fluid, whereas the ions are represented by macroparticles. Therefore, this model is able to resolve effects that are associated with the finite ion gyroradius, such as non-Maxwellian velocity distribution functions. Since the key features of our hybrid code are discussed in our preceding publications [cf. Simon et al., 2008a, 2008b, and references therein], we shall provide only a brief overview of the major input parameters for the Tethys simulations.

[6] The simulations were carried out with respect to the Tethys interaction system shown in Figures 1a–c. The characteristic parameters of the impinging magnetospheric plasma have been chosen close to the values suggested by Khurana et al. [2008]: The moon is exposed to an ideally corotating flow with a relative velocity of $u_0 = 34$ km/s and an upstream magnetic field strength of $B_0 = (0, 0, -167)nT$. The impinging plasma is assumed to consist of a single ion species of mass $m = 17$ amu, its number density being $n_0 =$
30 cm⁻³. The ion temperature has been set to $kT_i = 50$ eV. As will be discussed below, the density gradient term in the electric field equation of the hybrid model,

$$E = -\mathbf{u}_0 \times \mathbf{B} + \frac{(\nabla \times \mathbf{B}) \times \mathbf{B}}{\rho_0 e n} - \frac{2kT_i}{e n_0} \nabla n$$

(1)

([Simon et al., 2007], $\mathbf{u}_0$ is the ion bulk speed), plays a decisive role for the outcome of the simulation. Therefore, simulations with two different electron temperatures have been carried out: (i) $kT_e = 80$ eV and (ii) $kT_e = 20$ eV. In both scenarios, Tethys is exposed to a supersonic, yet subalfvenic and submagnetosonic plasma flow. As will be discussed below, the density gradient term also covers the effects caused by ambipolar electric fields in the moon’s wake. Therefore, $kT_e$ should rather be considered a measure for the weight of the density gradient term in equation (1) than a real physical temperature.

[7] In order to achieve a good coverage of the wakeside plasma structures, Tethys has been displaced from the center of the simulation domain. The spatial discretization in all simulations is realized by means of an equidistant Cartesian grid with a resolution of $\Delta_x = 0.06R_T (R_T = 533 \text{ km})$. Note that this value is comparable to the ion gyroradius of $r_g = m u_0/(eB_0) = 0.07 R_T$ in the impinging magnetospheric plasma. Due to the high thermal velocity of the impinging magnetospheric flow ($v_\text{th} = \sqrt{3kT_i/m} = 29.1 \text{ km/s} = 0.85 u_0$) and the small magnitude of the field distortions measured by Cassini (about 1 nT over a background field of 167 nT, cf. Figure 2), a very large number of 60 macroparticles per cell is required in order to quantitatively reproduce Cassini MAG observations. Otherwise, the simulated magnetic field distortions would simply be buried within the thermal background noise of the hybrid simulation. The boundary conditions applied to the obstacle’s interior are discussed by Roussos et al. [2008].

3. Simulation Results

[s] The simulation results for the case (i) scenario are displayed in Figure 2 and in Figure 3 (top). Figure 2 shows the comparison between simulation results (red) and MAG data (blue). In order to see the perturbations caused by the presence of Tethys more clearly, the spatially inhomogeneous dipole field of Saturn has been removed from the MAG dataset by subtracting a running average of 600 s, (cf. Khurana et al. [2008] for details). The output of the simulation model has been detrended analogously by sub-
tracting the background field \( B_0 \). The global structure of the plasma interaction region is shown in Figure 3.

As can be seen Figure 3 (top), the overall features of the interaction between an inert moon and a submagneto-sonic plasma flow are well reproduced by the simulation model. The magnetic field lines are drawn into the density rarefaction region at the wakeside of Tethys in order to compensate for the plasma pressure deficit (Figures 3b and 3d), giving rise to a magnetic rarefaction front at either side of the moon’s wake (Figure 3d). Both the field enhancement and the density cavity are elongated along the magnetic field direction, thus proving qualitatively that even significantly above and below Tethys, a noticeable distortion of the plasma should be measurable. In contrast to this, the plasma depletion region and the magnetic enhancement in the equatorial plane are confined to the moon’s geometric wake (cf. Figures 3c and 3d). It is also interesting to notice that the structure of the interaction region is highly symmetric in the \((x, z)\) plane, while a slight asymmetry with respect to the direction of the convective electric field can be identified in the equatorial plane. The relative magnitude of the magnetic field enhancement and consequentially, the sharpness of the corresponding rarefaction region seem to be more prominent at the Saturn-facing side of Tethys. This result is consistent with earlier findings in our simulations of Rhea’s plasma interaction [Roussos et al., 2008]. In any case, the reader should notice the very small magnitude of the field distortions, as indicated by the narrow range covered by the color bars.

Although the measured \( B_x \) component shows some signs of wave activity (which does not emerge from Tethys [cf. Khurana et al., 2008]), no sharply pronounced break-in or overshoot was detected (cf. Figure 2a). In other words, the magnetic field lines do not drape around an inert obstacle, but they pass through its solid body unaffected. Below Tethys, draping would cause a large positive \( B_z \) value. This behavior is well confirmed by the simulation model. The position and magnitude of the Saturn-facing rarefaction region, as indicated by the slight increase of \( B_y \), just before CA, have shown to be quantitatively reproducible as well. Although the model field subsequently exhibits a small dip, the magnitude and width of the second rarefaction region seem to be underestimated by the hybrid approach. Because Cassini’s distance to Tethys increased while passing through the wake, it intersected the anti-Saturn-facing rarefaction region further downstream than the Saturn-facing one. Thus, the magnitude of the \( B_y \) distortions detected at either side should not be the same. Quantitatively, this effect seems to be overestimated by the hybrid model. On the one hand, the overall asymmetry in the structure of the interaction region (with respect to the direction of the electric field) could be overestimated. Possible reasons for this are discussed in the final section. On the other hand, the number of macroparticles in the simulations may still be too low to reproduce all features of the very weak field perturbations detected southward of Tethys. However, as shown in Figure 2c, excellent quantitative agreement is achieved for the \( B_z \) component. The magnitude as well as the location of the field compression in the wake have shown to be fully reproducible by the simulation model. Although the measured field strength \(|B|\) is of course strongly perturbed by the wave signatures in the \( B_e \) component, the magnitude of the simulated field enhancement is again well confirmed by spacecraft data. To the authors’ knowledge, this is the first time that such weak field distortions have been reproduced within the framework of a hybrid simulation.

4. Discussion and Concluding Remarks

Although the quasi-neutral hybrid model has proven to be capable of reproducing MAG observations in the wake of Tethys, initial results from full-particle codes [Birch and Chapman, 2001] show that the assumption of quasi-neutrality may not be valid in the wake of an inert moon. As discussed, e.g., by Kallio [2005] for the lunar plasma
interaction, due to their higher thermal velocity, electrons from the adjacent flow tend to fill the wake faster than the ions. This leads to a violation of quasi-neutrality at the moon’s wakeside and hence, an ambipolar electric field is formed, pointing into the wake region. Although the hybrid approach cannot describe this effect self-consistently, the role of the ambipolar electric field is partially taken by the density gradient term in the electric field equation, cf. Figures 3(e)–(h) and 4. This is consistent with the lunar wake model of Kallio [2005]. The electric force arising from this term is directed into the wake, pointing perpendicular to the undistorted upstream flow direction. Thus, it makes the ions refill the wake. Since the magnetic field lines are transported by the plasma, it is also responsible for generating the field enhancement at the moon’s wakeside. Kallio [2005] shows in his study of the lunar plasma environment that the overall picture of the interaction is not changed, when the weight of the density gradient term in the electric field equation (i.e., $kT_e$) is reduced. As implied by the results of the second run (cf. Figures 3(e)–(h)), this finding seems to be valid in the case of submagnetosonic upstream flow as well. Despite the reduced influence of the density gradient term, there is still an extended magnetic field enhancement at the moon’s wake-
side. Nonetheless, as can be seen by comparing Figures 3b and 3f, the relative magnitude of the field distortion has clearly diminished. The opening angle of the cone-like wake is also slightly reduced. Of course, with respect to the strong background field, these effects can be considered negligible. However, it should be noted that none of the signatures observed along Cassini’s trajectory could be reproduced by the second simulation (results along trajectory not shown here). In other words, although the density gradient term takes only minor influence on the overall structure of the wake region, its weight in the electric field equation is of extreme importance for a quantitative comparison to spacecraft data, at least in the submagnetosonic flow regime. The influence of this term is also illustrated in Figure 4, displaying the component of the ion bulk velocity along the undisturbed magnetic field direction. This quantity provides a measure of ion acceleration into the central plasma wake. For $z < 0$, $u_z$ is directed upward, while in the $z > 0$ half space, the particle acceleration points downward. This gives rise to two counter-streaming ion beams which are responsible for refilling the depletion region at the moon’s wakeside. As can be seen, ion acceleration into the wake is significantly stronger when the temperature of the electron fluid is increased. In order to describe the refilling of the wake self-consistently, a fully kinetic simulation approach is required [see, e.g., Birch and Chapman, 2001]. So far, this kind of model is available only in one or two spatial dimensions, i.e., the asymmetries in the wake structure are not considered.

To sum up, the results presented above demonstrate that hybrid modeling is in general applicable to describe the interaction between Tethys and Saturn’s magnetospheric plasma. However, since quasi-neutrality of the plasma is enforced in this approach, the description of the wake structure cannot be expected to be in full quantitative agreement with the real situation. Another possible source of discrepancies between simulation and measurement could be the negligence of the spatially inhomogeneous dipole field in the model.

References


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![Figure 4](image-url)