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RESEARCH ARTICLE

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Key Points:

- Alfvén wings are expected near conducting moons but are not expected in an interaction of an inert moon with plasma
- Rhea is an inert moon, but in two close and a distant flyby, we observed Alfvénic structures in its wake
- We show that the wake refilling process generates a plasma pressure gradient that slows plasma in the wake and generates Alfvén wings

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The role of plasma slowdown in the generation of Rhea's Alfvén wings

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Abstract Alfvén wings are known to form when a conducting or mass-loading object slows down a flowing plasma in its vicinity. Alfvén wings are not expected to be generated when an inert moon such as Rhea interacts with Saturn's magnetosphere, where the plasma impacting the moon is absorbed and the magnetic flux passes unimpeded through the moon. However, in two close polar passes of Rhea, Cassini clearly observed magnetic field signatures consistent with Alfvén wings. In addition, observations from a high-inclination flyby (Distance > 100 R_{Rh}) of Rhea on 3 June 2010 showed that the Alfvén wings continue to propagate away from Rhea even at this large distance. We have performed three-dimensional hybrid simulations of Rhea's interaction with Saturn's magnetosphere which show that the wake refilling process generates a plasma density gradient directed in the direction of corotating plasma. The resulting plasma pressure gradient exerts a force directed toward Rhea and slows down the plasma streaming into the wake along field lines. As on the same field lines, outside of the wake, the plasma continues to move close to its full speed, this differential motion of plasma bends the magnetic flux tubes, generating Alfvén wings in the wake. The current system excited by the Alfvén wings transfers momentum to the wake plasma extracting it from plasma outside the wake. Our work demonstrates that Alfvén wings can be excited even when a moon does not possess a conducting exosphere.

1. Introduction

Rhea with a mean radius of 763.8 km is the second largest satellite of Saturn. A mean density of 1.236 ± 0.005 g/cm³ implies that its interior contains a rock metal fraction of ~25%, whereas a normalized axial moment of inertia of 0.3911 ± 0.0045 hints at an interior which is mostly nondifferentiated [*Anderson and Schubert*, 2007]. The surface of Rhea is heavily cratered and the average cratering model ages derived from the plains are on the order of 3.6-4.2 Gyr [*Neukum et al.*, 2005; *Zahnle et al.*, 2003]. Spectral observations of the surface in the visible to infrared frequencies show that Rhea's surface is less contaminated by exogenous materials such as CO_2 and hydrocarbons derived from Saturn's E ring than is Dione's surface [*Scipioni et al.*, 2014], because Rhea is located in the more tenuous part of Saturn's E ring. Scipioni et al. also show that there is much less asymmetry in terms of albedo and ice grain size between the leading and trailing hemispheres of Rhea compared to Dione, presumably for the same reason. The trailing hemisphere of Rhea is marked by several large bright filaments called wispy terrain which were thought to have a cryovolcanic origin [*Smith et al.*, 1981]. However, high-resolution images from Cassini reveal that the region is composed mainly of troughs and grabens with deposits of resurfaced bright ice covering the scarps [*Wagner et al.*, 2007, 2010]. Thus, Rhea appears to be a geologically inactive moon and no active internal sources of plumes or atmosphere generation are expected to be currently present on this moon.

The tenuous O_2 and CO_2 exosphere measured by Cassini during its 2 March 2010 flyby [*Teolis et al.*, 2010] corroborates this picture of a nonactive moon. The estimated mean column density of O_2 from this flyby was $\sim 3 \times 10^{16}/m^2$ which is 2 orders of magnitude below that encountered at Europa or Ganymede [*Teolis et al.*, 2010] and 4 orders of magnitude below the water column density observed at Enceladus [*Hansen et al.*, 2011]. With such a weak source of ambient neutrals, plasma production and loss is also expected to be minimal at Rhea. For example, the peak ion flux was measured to be $j \approx 10^{11}$ particles m⁻² ster⁻¹ s⁻¹ during the first flyby of Rhea [*Teolis et al.*, 2010] and lasted over a segment of ~200 km of the flyby. Assuming that the source extended over a length $L=2R_H$ in the direction transverse to the trajectory

©2017. American Geophysical Union. All Rights Reserved. (most likely an overestimate), the upper limit on the escaping number flux is $\dot{n} = 8\pi j L R_{RH} \approx 2 \times 10^{23}$ /s which translates into an upper limit on mass outflow of only 10 g/s assuming an average mass of 18 AMU for the ions. *Simon et al.* [2012] have calculated the implied height integrated Pedersen conductance of Rhea using the neutral density model of *Teolis et al.* [2010] and place an upper limit of 0.43 S on its value which is a factor of ~50 smaller than the Alfvén conductance of the plasma in Rhea's environment. Thus, both remote sensing and in situ measurements of Rhea's atmosphere suggest that Rhea appears neither a conducting (because of the noncollisional nature of its very sparse exosphere) nor a mass-loading object to the corotating plasma of Saturn's magnetosphere.

Rhea is located in the inner magnetosphere of Saturn at an average radial distance of $8.74 R_S$ (1 R_S = average radius of Saturn = 60,268 km). The local plasma density in the magnetosphere near Rhea is between 4 and 8 cm⁻³ [*Wilson et al.*, 2008; *Persoon et al.*, 2013; *Roussos et al.*, 2012] and consists mostly of water group ions produced by the Enceladus plume source. Because the Keplerian speed of Rhea is much lower than the corotating plasma, the plasma overtakes Rhea at a relative speed of ~57 km/s and predominantly strikes its trailing hemisphere. Saturn's magnetospheric field is directed predominantly southward and has a strength of ~20 nT near Rhea. The Alfvénic and magnetosonic wave speeds of the plasma are 46 km/s and 65 km/s. As the magnetosonic Mach number of plasma is lower than unity, no upstream shock is expected to be generated during the interaction.

Cassini has made four close flybys (CA distance $< 5 R_H$) and a distant flyby of Rhea. The first close flyby (R1) occurred on 26 November 2005 and took Cassini through Rhea's central wake. This flyby confirmed the picture of Rhea as an inert moon that intercepts the corotating plasma and creates a plasma depleted region in the downstream region [Khurana et al., 2008]. The observations showed that magnetic field passes through the inert moon unimpeded and gets further strengthened in the wake region in order to conserve total (magnetic + thermal) pressure. The next two close flybys (R2 on 2 March 2010 and R3 on 11 January 2011) were polar flybys and have been analyzed by Simon et al. [2012] and recently by Teolis et al. [2014]. These flybys confirmed that the field is indeed strengthened on field lines that are in contact with Rhea and have lost plasma. In addition, two new surprises emerged from these flybys, which are as follows: (1) an Alfvénic perturbation is formed in the wake side of Rhea [Simon et al., 2012], a topic we revisit in this work, and (2) near the equatorial edges of Rhea, a sharp field-aligned current system forms from the asymmetric precipitation of ions and electrons onto Rhea because of their differing gyroradii [Teolis et al., 2014]. Ions precipitate more uniformly onto Rhea because of their large gyroradii, while the electrons are constrained to flow north/south along the field lines. This difference creates a flow of ions toward the equatorial plane of Rhea to replenish the ions lost in that region. The resulting charge imbalance on Rhea's surface is remedied by field-guided electrons that precipitate onto Rhea's low-latitude rim [Teolis et al., 2014].

The fourth (and final) close flyby of Rhea (R4) which took Cassini on a highly inclined (moving south to north) trajectory with a closest approach on the anti-Saturn side occurred on 9 March 2013 (CA distance = $2.31 R_H$) and did not display any moon-related perturbations as expected for such a trajectory. However, a flux interchange event that occurred a few minutes after the CA makes it difficult to draw any definite conclusions. In this work, we will further analyze the magnetic field and energetic particle data from the R2 and R3 polar flybys of Rhea to understand the Alfvénic perturbations generated in the wake. Cassini Plasma Spectrometer (CAPS) instrument did not detect pickup ions during the polar flybys [*Teolis et al.*, 2010], though we note that the instrument pointing was not optimal for such a detection. Valuable energetic particle data from the MIMI/LEMS instrument were obtained during these flybys and are analyzed in this study. Next, we show that Cassini fortuitously passed through Rhea's Alfvén wing on a distant flyby (CA distance = $102 R_{RH}$) on 3 June 2010. The distant flyby confirms that momentum is exchanged between the plasma in the wake and the plasma outside of the wake on field lines that pass through the wake. Finally, we present results from a state-of-the-art, hybrid simulations to understand the behavior of plasma in the wake and the generation of Alfvén wings.

2. Trajectories and Observations

Figure 1 shows the trajectory of Cassini during the R2 and R3 flybys in a Rhea-centric coordinate system called RHIS (RHea Interaction System) described in the figure caption. The spacecraft traveled over the north pole of Rhea during the R2 flyby (CA distance = $1.13 R_{RH}$) and below the south pole during the R3 flyby (CA

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Figure 1. The trajectory of Cassini (red arrows) during the two polar flybys of Rhea. Near the closest approach, the spacecraft was located on field lines which are connected to Rhea. Sharp field-aligned currents were observed near the edges of Rhea. Rhea's size has been greatly exaggerated with respect to Saturn. Also illustrated is the coordinate system called the Rhea interaction system (RHIS, green arrows) whose x axis points along the corotation direction of plasma, y axis points toward Saturn, and the z axis lies along the spin pole of Saturn. The coordinate system is centered at the moon's center, and the distances in this coordinate system are measured in terms of Rhea radii (R_{Rh}).

distance = 1.09 $R_{\rm BH}$). Near the closest approach, the spacecraft was located on field lines that intersected Rhea and had lost some of their plasma.

Figure 2 shows magnetic field data from the R2 flyby in the RHIS coordinate system. The most noticeable aspect of the figure is the ~2 nT enhancement of field strength during the interval when the spacecraft was located on field lines intersecting Rhea. As discussed by Khurana et al. [2008] and Simon et al. [2012], field enhancements occur on field lines that are either in contact with Rhea or were in contact with Rhea in the past (i.e., on flux tubes encountered in Rhea's wake) and have lost plasma. This can be understood from the viewpoint of force balance in the vicinity of Rhea. As the gradients of plasma pressure p and magnetic pressures $(B^2/2\mu_0)$ are two of the dominant forces in Rhea's environment and oppose each other, one expects



Figure 2. Magnetic field observations in Rhea Interaction System (RHIS) coordinates during the northern R2 flyby. The spacecraft remained downstream and north of Rhea ($Z > 1.1 R_H$) during the closest approach segment. The vertical solid lines mark the times when the spacecraft was located at Y = -1 R_{RH} and Y = 1 R_{RH} , respectively. The dashed lines represent the background field near Rhea and were obtained by fitting first-order polynomials to observations in the vicinity of Rhea from which near-Rhea ($R < 2.5 R_{BH}$) observations were excluded. The CA occurred at 17:40:36.



Figure 3. Magnetic field observations in Rhea Interaction System (RHIS) coordinates during the southern R3 flyby. The spacecraft remained downstream and south of Rhea ($Z < -1.04 R_H$) during the closest approach segment. The vertical solid lines mark the times when the spacecraft was located at $Y = -1 R_{RH}$ and $Y = 1 R_{RH}$, respectively. The dashed lines represent the background field near Rhea and were obtained by fitting first-order polynomials to observations in the vicinity of Rhea from which near-Rhea ($R < 2.5 R_{RH}$) observations were excluded. The CA occurred at 04:53:34.

or

$$\left(p + \frac{B^2}{2\mu_0}\right) \approx \text{const}$$
 (2)

Thus, any reduction in plasma pressure caused by particle loss is compensated by an increase of magnetic field strength in that region. The other two remarkable features in the observations are two sharp field rotations observed in the B_x component around hours 17:39 and 17:42 caused by localized pairs of field-aligned currents. *Teolis et al.* [2014] have shown that the sharp current system results from differences in ion and electron gyroradii and the requirement to balance currents on the sharp Rhea surface. The ions, because of their large gyroradii, precipitate (almost) uniformly on to Rhea from all directions, while the electrons are constrained to move north/south along the field lines. This difference in precipitation pattern causes a deficit of ions in the region surrounding Rhea. On field lines in this near-contact region, ions move along the field (both from north and south) to compensate for this loss near Rhea, creating a field-aligned current directed toward the equatorial plane of Rhea. Similarly, to compensate for the ion deposition on Rhea, electrons move along the field lines that are in direct contact with Rhea creating an oppositely directed current to that of ions (directed away from Rhea's equatorial plane). The current system is closed at large distances from Rhea by whistler type waves [*Teolis et al.*, 2014]. Indeed, *Santolík et al.* [2011] have reported the presence of such whistler type waves in the RPWS (Radio and Plasma Wave Science) data collected from the R2 flyby during the interval when Cassini was located on flux tubes connected to the surface of Rhea.

A final remarkable feature of the observation is the negative B_x perturbation observed on field lines that are in contact with Rhea. As pointed out by *Simon et al.* [2012], this feature is caused by an Alfvénic perturbation and is reminiscent of Alfvén wings usually observed at mass-loading bodies such as lo or Enceladus from plasma loading [*Neubauer*, 1980, 1998; *Khurana et al.*, 2007]. Indeed, the draping of field around an obstacle creates a negative B_x field above the draping center (z > 0) and a positive B_x component below it, consistent with observations at Rhea. We return to the question of how the Alfvén wing is generated in the absence of mass loading, later.

Observations from the R3 flyby which traversed Rhea over its southern pole are shown in Figure 3 and confirm the findings from the R2 flyby. The magnetic field is again enhanced within the flux tubes that are



Figure 4. (top) Energetic electron fluxes from the C1 channel (27–48 keV) of Cassini MIMI/LEMMS instrument and magnetic field observations from Cassini magnetometer during the R2 and R3 flybys. The vertical dashed lines mark the region between $-1R_{RH} < Y_{RHIS} < 1R_{RH}$.

in contact with Rhea and have lost plasma. The sharp current systems generated by the precipitation of ions onto Rhea from adjacent flux tubes are also present on field lines that traverse the equatorial boundary of Rhea. Finally, a positive B_x component (opposite to that of R2 flyby) is observed on field lines for which $X_{HIS} > 0$, expected of an Alfvén wing.



Figure 5. (first panel) Energetic electron observations from C0 to C4 channels of MIMI/LEMMS instrument and (second to fourth panels) magnetic field observations (in RHIS coordinates) from the Cassini magnetometer during the distant flyby of Rhea's Alfvén wing which occurred on 3 June 2010. The spacecraft was at a distance of $102 R_{RH}$ from Rhea during the Alfvén wing encounter. The spacecraft was southward ($Z_{RHIS} = -69.3 R_{RH}$) and well downstream ($X_{RHIS} = 66.5 R_{RH}$) of Rhea during the encounter.



Figure 6. The trajectory of Cassini in RHIS coordinate system (thick black line) during 18:30–20:00 on 3 June 2010. The black solid circle marks the passage through the Alfvén wing. The southern part of the Alfvén wing is drawn with a dashed line which corresponds to an Alfvén Mach number of 0.96.

In Figure 4, we compare and contrast the observations from the two polar flybys by plotting them against the Y_{RHIS} coordinate. Also plotted are differential fluxes in the 27–48 keV electron channel observed by the MIMI/LEMMS instrument. A clear correlation is observed between particle loss and field enhancement (as seen in more negative B_z component). The reversal of the B_x perturbation between the two flybys is also amply clear, demonstrating that the draping center (where B_x reverses) is located near the equatorial plane of Rhea.

One of the key questions about the observed Alfvénic perturbations is whether they are local in extent, with the current systems confined in the immediate region surrounding Rhea, or connect the source region near Rhea to Saturn's ionosphere (the ultimate source of angular momentum for the Kronian plasma). An examination of field and particle data from the vicinity of Rhea revealed that during a distant pass of Rhea on 3 June 2010, Cassini crossed the Southern Alfvén wing of Rhea when it was at a radial distance of 102 $R_{\rm RH}$ from Rhea, suggesting that the Alfvénic perturbations indeed continue to large distances and very likely close in Saturn's ionosphere. Figure 5 shows magnetic field and energetic

electron observations while Figure 6 shows the spacecraft trajectory during this crossing. It can be seen that during the crossing, all five energetic electron channels (energies 18–183 keV) observed electron flux depletions (see Figure 5, first panel), as would be expected of Saturn's flux tubes that had earlier come into contact with Rhea and had become depleted of energetic electrons. The magnetic field data (in Saturn-centered spherical coordinates) show a clear positive B_{φ} perturbation (implying $B_x > 0$) as expected from an Alfvén wing propagating southward. The B_{φ} perturbation has a magnitude of ~0.7 nT (roughly one third of the amplitude observed near Rhea during R2 and R3 flybys). To some extent, the reduction in the Alfvén wing amplitude is caused by the increase of Alfvén velocity away from the center of Saturn's plasma sheet (we estimate the local Alfvén velocity to be twice that observed near Rhea) because the wave energy flux ($B_x^2/\mu_0 \times V_A$) must be conserved.

In order to establish the source location of the Alfvén wing, we have traced the perturbation region back to the equatorial plane of Rhea along the southern Alfvén wing characteristic given by

$$\mathbf{V}_{\mathsf{A}}^{+} = \mathbf{V}_{\mathsf{0}} + \mathbf{B}_{\mathsf{0}}/\sqrt{\mu\rho} \tag{3}$$

and overplotted it on Figure 6 (top, dashed line). Here we chose $\mathbf{B}_0 = (0, 0, 25 \text{ nT})$, and an average plasma density, $n = 5/\text{cm}^3$ [Wilson et al., 2008; Persoon et al., 2013]. The Alfvénic Mach number is estimated to be ~0.96 (assuming an average mass of ion to be 17 proton masses and plasma velocity, $\mathbf{V}_0 = (57, 0, 0)$ km. The angle θ_A between \mathbf{B}_0 and \mathbf{V}_A^+ is thus equal to 44°. Here we have used field and plasma parameters that are averaged over the extent of the Alfvén wing. Away from the center of Saturn's plasma sheet, where the

 Table 1. Magnetic Field and Plasma Conditions Near Rhea Used in

 Hybrid Simulations

Parameter	Values for R2	Values for R3
lon number density	7/cm ³	7/cm ³
Bulk velocity	(50,0,0) km/s	(50,0,0) km/s
External magnetic field	(4.5, 1.7,-20.0) nT	(1.0, 0.5,-20.0) nT
lon temperature	200 eV	100 eV
Electron temperature	10 eV	10 eV
Plasma beta	1.4	0.7

Alfvén wing signature was discovered (Saturn latitude -6°), the plasma density is expected to be lower (by a factor of 2) and the observed field strength (~30 nT) is slightly higher. Thus, the value of θ_A used in Figure 6 is a rough average. With this choice of field and plasma parameters, we find that the Alfvén wing is connected to the wake of Rhea and not Rhea itself. However,

we caution the reader that the uncertainties in our knowledge of the plasma parameters are quite large and the only definitive conclusion that can be drawn from this mapping is that for a range of reasonable choices of field and plasma parameters, the origin of the Alfvén wing from the wake is not excluded. We also note here that the Alfvén wing was not observed at $Y_{RHIS} = 0$, but further inward toward Saturn. This is expected because the Alfvén wave packet travels toward Saturn along the field line as it moves away from Rhea. The observed location of the Alfvén wing at $Y_{RHIS} = 31 R_{RH}$ is roughly consistent with the local field line geometry such that $|B_y/B_z| = |dy/dz| \approx |Y_{RHIS}/Z_{RHIS}| \approx \frac{1}{2}$.

As discussed above, Rhea is a nonconducting object and also does not mass load the interacting plasma appreciably. Therefore, the discovery of an Alfvén wing in Rhea's wake in the absence of these "traditional" sources of field draping is indeed very surprising. *Simon et al.* [2012] have suggested that the plasma density gradient arising from the finite extension of Rhea's wake creates a diamagnetic current J_{dia} according to the relation

 $J_{dia} =$



Figure 7. Magnetic field observations from the R2 flyby (black lines) and results from our hybrid simulation (red lines) in the RHIS coordinate system described in Figure 1.

$$\frac{\mathbf{B} \times \nabla p}{B^2} \approx \frac{1}{B_0} \frac{\partial p}{\partial x} e_y \tag{4}$$

where they justifiably assumed that the perturbation field is weak, so that |B| $= |\mathbf{B}_0|$. Simon et al. suggest that such a diamagnetic current is responsible for generating the Alfvénic perturbations observed in Rhea's wake. We do not disagree with Simon et al. that diamagnetic currents are generated near Rhea in response to the pressure gradients that are set up in the wake. However, we observe that in most situations, the diamagnetic currents tend to close locally around the source of diamagnetism and do not propagate away from the source as field-aligned currents. The exception to this rule, as discussed by Vasyliunas [1970], is a situation where the plasma pressure gradient has a component along the direction of $\mathbf{B} \times \nabla B$ drift of particles. Such a situation occurs in a partial ring current in a magnetosphere where the nonuniform (dipolar) magnetic field sets up a $\mathbf{B} \times \nabla B$ drift of particles in the azimuthal direction and any pressure anomaly in that direction leads to the generation of a field-aligned current that closes into and out of the ionosphere at the edges of the partial ring current.



This situation does not apply to Rhea's interaction with Saturn's magnetosphere where over the length scale of Rhea, the background field is essentially uniform (and assumed as such by Simon et al. in their simulation). On the other hand, we have now observed the Alfvénic perturbation far away from Rhea (x distance ~70 R_H) where the wake has dissipated. The observed field perturbation at this large distance is reminiscent of Alfvénic wings that transfer momentum between two plasma populations such as the stationary ionosphere of a moon and the flowing plasma of a magnetosphere. We therefore suspect that the origin of the Alfvén wings lies in plasma slowdown created by the pressure gradient force, a term ignored by Simon et al. [2012]:

$$\rho \frac{\mathrm{d} \mathbf{v}}{\mathrm{d} t} = -\nabla p + \mathbf{J} \times \mathbf{B}$$
 (5)

Equation (5) states that the pressure gradient force would accelerate plasma in the -x direction (toward Rhea), in opposition to the background plasma flow and would thus slow it down. In this scenario, the Alfvén wings would

Figure 8. Magnetic field observations from the R3 flyby (black lines) and results from our hybrid simulation (red lines) in the RHIS coordinate system described in Figure 1.

be generated in the wake to bring the slowed wake plasma back to corotation speed. Thus, reliable plasma flow velocity measurements near Rhea would be of great value in unraveling the mystery of Alfvén wings near Rhea. Unfortunately, because both the ion flux counts are extremely low in the wake and the time resolution of the CAPS instrument is quite low (several minutes for each distribution function), it was not possible to obtain reliable estimate of plasma flow in the wake. We will therefore rely on fully self-consistent hybrid simulations to infer the properties of plasma flow in the vicinity of Rhea and arrive at an understanding of stress balance in the plasma surrounding Rhea.

3. Hybrid Simulations

In this work, we use a three-dimensional hybrid plasma simulation first introduced by *Holmström et al.* [2012] for studies of solar wind interaction with the Moon. In this model, ions are treated as positively charged macroparticles and electrons are a massless charge-neutralizing fluid. The ion trajectory is obtained from the ion momentum equation:

$$\frac{d\mathbf{v}}{dt} = \frac{q}{m} (\mathbf{E} + \mathbf{v} \times \mathbf{B}) \tag{6}$$

where *q*, *m*, and **v** are ion charge, mass, and velocity, respectively, **E** is the electric field, and **B** is the magnetic field. We treat Rhea as a highly resistive (conductivity $\sigma = 10^{-7}$ S/m), plasma-absorbing body. The electric field is given by

$$\mathbf{E} = \frac{1}{\rho_{I}} \left(-\mathbf{J}_{I} \times \mathbf{B} + \mu_{o}^{-1} (\nabla \times \mathbf{B}) \times \mathbf{B} - \nabla \rho_{e} \right) + \nabla \times \mathbf{B} / (\mu_{0})$$
(7)

Where ρ_l is the ion charge density, \mathbf{J}_l is the ion current, p_e is the electron pressure, and μ_o is the magnetic permeability of free space. Here electron pressure p_e is assumed to be adiabatic with an adiabatic index $\gamma = 5/3$, such that



Figure 9. (a, c, and e) XY plane (at Z = 0) and (b, d, and f) XZ plane (at Y = 0) cuts through our simulation box for normalized plasma density (Figures 9a and 9b), normalized plasma velocity (Figures 9c and 9d) and normalized magnetic field (Figures 9e and 9f). The wake extends to a downstream distance of at least 4 R_{RH} before dissipating.

$$\frac{p_e}{p_{e0}} = \left(\frac{n_e}{n_{e0}}\right)^{\gamma} \tag{8}$$

where the zero subscript denotes the reference value at the inflow boundary upstream of Rhea. The magnetic field is advanced using the Faraday's law:

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} \tag{9}$$

We use a uniform Cartesian grid with $108 \times 108 \times 144$ cells (each with a scale size of 95 km) and discretize the spatial derivatives using a standard second-order finite difference scheme. The simulation has open inflow/outflow boundaries in X and periodic boundaries in Y and Z. The calculations are advanced in time by a predictor-corrector method using cyclic leapfrog method, as explained by *Holmström et al.* [2012], [see also *Matthews*, 1994]. Further information of the numerical model can be found in *Holmström* [2010]. The upstream field and plasma conditions used in the simulation are given in Table 1.

Figures 7 and 8 show a comparison of magnetic field observations and simulation results. As can be seen, the simulation reproduces all three components of the magnetic field quite well and gives us confidence that our simulation is capturing the underlying physics correctly. Because of the low resolution of the grid used and also because full electron dynamics are not captured in our simulations (because electron pressure is a scalar in our equations as opposed to a tensor), we are unable to reproduce the sharp spikes at the edges of Rhea generated by the imbalance of surface current and the resulting field-aligned currents. However, the enhancement of the field strength by the plasma cavity and the B_x perturbation generated by the Alfvén wings are clearly present in our simulations. We note that in our model, Rhea's conductivity is extremely low ($\sigma = 10^{-7}$ S/m). In addition, there are no sources of plasma pickup. Therefore, we conclude that in our simulation, the Alfvén wings were not generated by these two "traditional" sources of plasma slowdown in the vicinity of a moon and we must look for other causes.

Figure 9 shows the normalized plasma density, velocity, and field strength in the XY plane (Z = 0, a, c, and e) and XZ plane (Y = 0, b, d, and f) of our simulation box. The formation of the wake from the absorption of



Figure 10. The magnitude of field line bend (in degrees) relative to the background field direction. The near constancy of field line bend in the downstream direction is consistent with the excitation source of Alfvén wings (namely, plasma slowdown) located in the wake region.

plasma by Rhea is extremely clear in plasma density (Figures 9a and 9b). Equally clear is the magnetic field enhancement that occurs in response to loss of plasma (Figures 9e and 9f). The wake is much wider in the direction of the magnetic field (Z direction) than across it, because in a submagnetosonic interaction, particles with large fieldaligned velocities that were initially located far above or far below the moon can precipitate onto the moon over the time the field line is in contact with the moon (as explained further by Khurana et al. [2008]; also, see their Figure 9) creating a wide field-aligned plasma shadow downstream. The most noticeable and surprising aspect of Figure 9 in this manuscript is the substantial decrease in plasma velocity (as much as 30% between 1 $R_{\rm Rh} < X < 2$ $R_{\rm Rh}$, see Figures 9c and 9d) in the wake region as we surmised earlier. The other feature in Figure 9 is the bending of the field lines in the wake region seen in the XZ plane (see panel Figure 9f, where we have traced magnetic field lines) clearly reminiscent of Alfvén wing type perturbations. In Figure 10, we have guantified the bend angle of the field lines observed in the wake region. The actual

bending of the field lines is quite modest (6° or less) suggesting a weak field-aligned current system. However, the front across which the bend occurs is clearly aligned with the Alfvén characteristics. The simulations thus unambiguously confirm that the source of Alfvénic perturbations is the plasma slowdown in the wake of Rhea. The plasma slowdown results undoubtedly by the action of the plasma pressure force in accordance with equation (5), $\rho \frac{d\mathbf{v}}{dt} = -\nabla p + \mathbf{J} \times \mathbf{B}$, where the plasma pressure force ($-\nabla p$) is directed in the -X direction, because in the near wake the plasma pressure is close to zero, but at large X distances ($>4R_{RH}$), the plasma density and therefore the plasma pressure have returned to their normal values. The pressure gradient force is in opposition to the direction of the background flow (+X) and thus decelerates it. A field line in the wake, therefore, has slower plasma on it near the equatorial plane of Rhea. However, at large Z values, the flow and the field line are moving at the full background plasma near the equatorial plane of Rhea. The momentum for this process is obtained from the background plasma in the Alfvén wings that ultimately close in the ionosphere of Saturn. Thus, we conclude that Saturn's ionosphere is the ultimate source of momentum for the weak Alfvén wings that are generated in Rhea's wake.

4. Summary and Conclusions

In this work we have shown that Alfvén wing type structures can form in the wake of an inert object such as Rhea. The primary cause of the formation of these structures is the plasma pressure reduction in the wake of the moon resulting from plasma absorption on field lines that come into contact with Rhea. Because of the low sonic and magnetosonic Mach numbers of upstream plasma, the wake gets refilled in a short downstream distance (typically 4–6 $R_{\rm RH}$) from plasma that flows along the field lines. However, in the near wake, the plasma pressure remains depressed compared to the far wake. The resulting pressure gradient

force is directed toward Rhea and decelerates the wake plasma. Outside of the plasma wake, the plasma moves at its background velocity generating an Alfvén wing that bends the magnetic flux tubes and transfers momentum from the ambient plasma to the wake. A distant high-inclination flyby encountered the Alfvén wing at a distance of $102 R_{Rh}$ revealing that the Alfvén wing currents are ultimately closed far away from Rhea, most likely in Saturn's ionosphere.

The discovery of momentum transfer mediated by Alfvénic perturbations in Rhea's wake suggests that such structures must also occur in the wakes of other inert moons such as Mimas, Dione, and Tethys. Recently, *Zhang et al.* [2014] using a comprehensive field and plasma data from the ARTEMIS mission (Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon's Interaction with the Sun mission) have shown that similar structures exist in the wake of the Earth's moon even though the solar wind is supermagnetosonic and the wake plasma depletion continues for at least 12 lunar radii. Those observations also confirmed that the solar wind is slowed down in the lunar wake, and Alfvénic perturbations are launched from the wake center. Thus, Alfvén wings should be considered ubiquitous in all situations where a moon interacts with a flowing plasma irrespective of whether the moon has a conducting exosphere or not.

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