Mass loading of Saturn’s magnetosphere near Enceladus

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[1] The Cassini spacecraft has made three close flybys of Enceladus. The magnetic field from the first flyby clearly showed that Enceladus acts as an obstacle to the magnetized flow resulting in field line draping. The second flyby confirmed the draping pattern but hinted that the effective source must be located below Enceladus and demonstrated that Enceladus does not possess a measurable internal magnetic field. In situ and remote sensing observations on the third flyby provided conclusive evidence of a large vent outgassing near the south pole of Enceladus and confirmed the southern offset of the center of draping. In this work, we model the magnetic field data collected from the three flybys in order to quantify the strength of the Enceladus/plasma interaction. We show that the effective diameter of the obstacle is at least 6 RE, and the obstacle is displaced by >2 RE south of Enceladus and downstream by at least ~1 RE. The total current produced in the interaction is <10⁵ Amps (40–60% of the Neubauer limit). We estimate that the mass picked up by the plasma within 5 RE of Enceladus is <3 kg/s. Additional pick up must be occurring in the neutral torus extending outward from the orbital location of Enceladus.


1. Introduction

[2] The small moon of Saturn, Enceladus (radius = 250 km), has long been suspected of harboring internal activity that renews its surface and helps provide material to the planet’s E ring [Smith et al. 1982; Horanyi et al., 1992]. How the moon is able to replenish the E ring has been a matter of great debate. Pang et al. [1984] suggested a deep volcanic mechanism, whereas Haff et al. [1983] favored geyser type activity in the ice shell. McKinnon [1983] suggested that a geologically recent asteroid impact on Enceladus created the E ring, while Hamilton and Burns [1994] argued that the fine dust of E ring arises from the collision of larger dust grains with Enceladus. In order to settle the debates, Cassini made three flybys of Enceladus in 2005. The first flyby (E3) occurred on 17 February (Cassini flybys of Enceladus are labeled with an “E” followed by the revolution number of Cassini’s trajectory about Saturn), and the magnetic field data collected during this flyby showed that Enceladus acts as an obstacle to the magnetized flow such that the field drapes around it [Dougherty et al., 2006]. The second flyby (E4) on 9 March confirmed the draping pattern but hinted that the effective source was located below Enceladus. Based on these findings, the Cassini Project lowered the flyby altitude of the third flyby (E11) on 14 July from 1000 km to 175 km. In situ and remote sensing observations from E11 provided conclusive evidence of a large vent outgassing near the south pole of Enceladus from a warm region which has seen recent geological activity [Porco et al., 2006; Spencer et al., 2006; Hansen et al., 2006; Spahn et al., 2006; Dougherty et al., 2006; Tokar et al., 2006; and Waite et al., 2006]. In this work, we further analyze the magnetic field data and present a modeling study of the data collected from the three flybys in order to quantify the strength of the Enceladus/plasma interaction.

2. Interaction of Enceladus With the Saturnian Plasma

[3] Enceladus is located in the inner magnetosphere of Saturn at a radial distance of 3.94 RE (1 RE = 60268 km) where the corotating plasma of Saturn’s magnetosphere overtakes Enceladus at a speed of 26 km/s. The magnetic field strength in this region is ~320 nT, and the electron density is ~60/cm³ [Richardson, 1998]. The background ions and electrons have temperatures of ~50 and 5 eV, respectively [Sittler et al., 1983; Saur and Strobel, 2005]. Because the plasma is derived mainly from water group ions, the average mass of an ion is ~17 AMU. The sonic and Alfvénic speeds in the local medium are therefore ~20 and 150 km/s, respectively. These speeds indicate that the interaction of Enceladus with magnetospheric plasma is both sub-Alfvénic and sub-magnetosonic.

[4] In addition to the charged particle population, the inner magnetosphere also contains a neutral cloud consisting of H₂O and OH molecules and O and H atoms and with a peak density of ~2000/cm³ just outside the orbit of Enceladus [Shemansky et al., 1993; Hall et al., 1996; Jurac and Richardson, 2005]. Detailed modeling by Jurac and

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Richardson shows that H₂O is the dominant neutral near the icy satellites but OH dominates elsewhere because H₂O rapidly dissociates by “collisions” with photons and electrons. Jurac and Richardson also found that even though all of major inner satellites contribute to the H₂O budget, most of the H₂O is derived principally from a “source” at Enceladus. New in situ observations from Cassini Ion and Neutral Mass Spectrometer (INMS) [Waite et al., 2006] and Cassini Plasma Spectrometer (CAPS) [Young et al., 2005; Sittler et al., 2005] and remote sensing observations from Ultraviolet Imaging Spectrograph (UVIS) [Hansen et al., 2006] are strongly suggestive that the Jurac and Richardson “source” of molecular H₂O is the south-pole plume of Enceladus.

[5] As the magnetospheric plasma of Saturn interacts with the Enceladus plume, new ions are created through electron impact ionization and photoionization processes and added to the corotating magnetospheric plasma flow. The newly formed ions extract momentum from the flow slowing it down. Additional slowing of the plasma occurs from charge exchange between the neutral cloud and the magnetospheric ions. This process leads to the generation of fast neutrals (which escape) and new ions which begin with Keplerian velocities and extract momentum from the flow as they are accelerated up to corotation velocities. Recent analysis by Burger et al. [2007] suggests that in the vicinity of Enceladus, charge exchange dominates over electron impact ionization and photoionization by a factor of ~100 in “mass loading” the flow. In this work, we use the term “mass loading” loosely to denote all newly born ions (whether from photo or electron impact ionization or from charge exchange) that extract momentum from the background flow.

[6] The slowed plasma in the mass-loading region generates thermal and magnetic pressure gradients and a curvature in the magnetic field which divert and accelerate the flow around the mass-loading region. In terms of currents, diamagnetic, Pedersen, and plasma pick up currents flow through the pick up region providing the required \( \mathbf{J} \times \mathbf{B} \) Lorentz force to accelerate the plasma. The current eventually closes in Saturn’s ionosphere, carried by a pair of Alfvénic disturbances (called the Alfvén wings) coupling Enceladus’ interacting plasma to the ionosphere of Saturn (see Figure 1). In the plasma rest frame, the disturbances propagate along the field line, but in the rest frame of the moon, they propagate along the Alfvén Mach angle as discussed by Neubauer [1980, 1998] for the Jovian satellites. The Alfvén-wing current system is responsible for enhancing the field upstream of the obstacle and draping it around the obstacle. The current system also reduces the field strength directly behind Enceladus in the wake, a region that has not yet been visited by Cassini. By modeling the currents implied by the magnetic field measurements in the interaction region, one can place limits on “mass loading” under certain assumptions.

[7] In this work, we shall use a Cartesian coordinate system called Enceladus Interaction System (ENIS) whose \( x \)-axis is directed along the corotating flow, \( y \)-axis points towardstoward Saturn, and the \( z \)-axis points along the rotational axis of Saturn. The cartoon of the interaction of a conducting/mass-loading obstacle with a magnetized flowing plasma. Notice that the sign of the observed \( B_y \) component can be used to determine whether the source region is above or below the spacecraft. The sign and magnitude of the \( B_y \) component indicate whether field-line draping is occurring around the mass-loaded object.

3. Trajectories and Observations

[8] Figure 2 shows the flyby trajectories in three orthogonal projections of the ENIS coordinate system. It can be seen that Cassini was upstream of Enceladus near the closest approach (CA) to Enceladus for all three flybys. Also shown in d are the magnetic perturbation vectors (observation background) projected into the \( x-y \) plane. The large region of space over which the perturbations are observed suggests that the mass-loading object is several times larger than Enceladus. It is clear from the magnetic field vectors that the flow has been slowed (enhancement in the field strength not shown but discussed further below) and diverted around an obstacle. The observed magnetic field perturbations are inconsistent with an origin internal to Enceladus because a scalar field should fall off as \( 1/r^3 \) or faster from Enceladus [Dougherty et al., 2006]. The perturbations however are consistent with an origin in an Alfvén-wing current system as discussed in the next section.

[9] Figure 3 shows a time plot of the vector magnetic field observed by Cassini during the E3 flyby. Near the CA, the spacecraft was upstream and north of Enceladus (positive \( Z \)) and traveled from \( +Y \) to \( -Y \) (i.e., radially outward from Saturn). The negative \( B_y \) perturbation and the positive to negative change in the sign of \( B_y \) as the spacecraft traveled from \( +Y \) to \( -Y \) indicates that the source is located...
below the trajectory (see Figure 1). No sharp rotations in the magnetic field were detected, suggesting that the trajectory did not cross either of the Alfvén wings. In addition to the Enceladus interaction signature, left-hand polarized waves with a period of $\frac{1}{C_24}$ s corresponding to the water group ions were also observed over most of the inner magnetosphere [Dougherty et al., 2006]. In order to understand these waves better, we subtract the background field from the observations (Figure 4). The background field is calculated by performing running averages over 1 minute of data and then shifting the averaging interval by a data point (1 s).

[10] The wave power in Figure 4 does not display a local enhancement near Enceladus. Leisner et al. [2006] have shown that these waves are generated by the erosion of E-ring neutral cloud material and are prevalent throughout the E ring over nearly all local times but are tightly confined to the equatorial plane of Saturn. The peak in the ion_cyclotron cyclotron wave power occurs near the radial distance of Enceladus. The energy for the waves is derived from the thermalization of recently picked up ions which have a ring distribution in velocity space. Because Cassini did not directly intercept the field lines on which the local pick up from the plume of Enceladus is occurring, a lack of local enhancement in the ion_cyclotron cyclotron wave power is understandable.

[11] Figure 5 shows the time series of the magnetic field from the E4 flyby which occurred on 9 March 2005. The spacecraft remained upstream and south of Enceladus during this encounter. Surprisingly, the perturbation in the $x$ component of the magnetic field is negative. A positive sign would be expected if Enceladus itself were the source of mass loading (see Figure 1). As discussed below, we now believe that the effective mass-loading region is located south of both Enceladus and the E4 trajectory. The field strength is enhanced as would be expected upstream of an obstacle that has slowed the plasma. As no discontinuous reversals in the magnetic field components corresponding to current sheet crossings were observed, the spacecraft must not have penetrated either of the Alfvén wings and the mass-loading region itself.

Figure 2. The trajectories of Cassini near Enceladus in three projections in the satellite interaction coordinates. Only those portions of the trajectories are shown which satisfied the criterion $-5 R_E < X, Y, Z < 5 R_E$. Also drawn is the nominal location of the cold plasma wake in the X-Y and X-Z projections. d shows the X-Y projection of the perturbation magnetic field vectors.
In order to understand the ion cyclotron waves better, in Figure 6, we show a plot of the detrended data by subtracting a background as outlined above. The wave power is seen to gradually decrease as the spacecraft traveled toward Saturn, most likely a result of decreasing speed at which the new ions are picked up [Leisner et al., 2006]. Again, we do not observe a local enhancement in the power of ion_cyclotron cyclotron waves at Enceladus.

![Figure 3.](image)

**Figure 3.** Magnetic field observed during the E3 flyby in the ENIS coordinate system over a period of 80 minutes near the closest approach to the moon. The variables listed below the magnetic field traces describe the trajectory of the spacecraft in moon radii. Notice that the vertical scales are different for each of the panels.

![Figure 4.](image)

**Figure 4.** The high-frequency magnetic field perturbations from ion cyclotron waves observed during the E3 flyby. The perturbation field was calculated by subtracting the background field from the observations as described in the text. The wave power does not peak near the closest approach to the moon.
This finding suggests that during this pass as well, the spacecraft did not directly encounter mass-loaded field lines.

Figure 7 shows the time series of the magnetic field from the E11 flyby that occurred on 14 July 2005. This upstream flyby brought Cassini within 200 km of Enceladus. At the CA, the spacecraft was located upstream and south of Enceladus but traveled rapidly in both $Y$ and $Z$ directions over the time interval plotted. Similar to the E4 flyby, a negative perturbation in $B_x$ is observed at CA which

![Enceladus 4](image)

**Figure 5.** Magnetic field observed during the E4 flyby in the ENIS coordinate system described in the text. The variables listed below the magnetic field traces depict the trajectory of the spacecraft. Notice that the vertical scales are different for each of the panels.

![Enceladus 4](image)

**Figure 6.** The ion cyclotron waves observed during the E4 flyby. The perturbation field was calculated by subtracting the background field from the observations as described in the text. The wave power does not peak near the closest approach to the moon.

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is compatible with a source located south of Enceladus but not at Enceladus itself. The detrended data of Figure 8 show the ion cyclotron waves calculated by using the scheme outlined above. In this case also, no wave power enhancements associated with Enceladus were observed. The sharp commencement of waves at 19:15 and cessation at 20:25 UT is most likely caused by the entrance into and exit of the spacecraft from the central dense plane of the E-ring.

**Figure 7.** Magnetic field observed during the E11 flyby in the ENIS coordinate system described in the text. The variables listed below the magnetic field traces depict the trajectory of the spacecraft. Notice that the vertical scales are different for each of the panels.

![Magnetic field observed during the E11 flyby](image)

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**Figure 8.** The ion cyclotron waves observed during the E11 flyby. The perturbation field was calculated by subtracting the background field from the observations as described in the text. Notice the strong confinement of the waves to the equatorial region of Saturn (|Z_{ENIS}| < 60 R_E = 0.25 R_S) where the neutral cloud of Saturn is found.

![The ion cyclotron waves observed during the E11 flyby](image)

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molecular cloud where the amplitudes of the ambient ion cyclotron waves peak [Leisner et al., 2006].

4. Biot-Savart Modeling

[14] In order to place limits on the strength of Enceladus’ interaction with the plasma in Saturn’s magnetosphere, we shall compute the magnetic field generated by the currents in the interaction region. We use a model of the current system first used by researchers to model Io’s interaction with Jupiter’s magnetosphere [Herbert, 1985; Khurana et al., 1997]. The model was originally devised for studying the Alfvénic interaction of a conducting object with a flowing magnetized plasma. Neubauer [1998] has shown that the model can be modified for the situation where mass loading is the dominant process by replacing the ion/neutral and electron/neutral collision frequencies with effective collision frequencies which also take into account the charge-exchange and electron impact ionization reactions. In this work, we do not model the conductivity of the medium self-consistently but use it as a free parameter whose value is implicitly related to the total current flowing in the interaction region.

[15] Figure 9 shows a cartoon representation of the model. For ease of calculation, the mass-loading region is assumed to be spherical. The plasma pick up and reacceleration currents flow across the plasma pick up region in the direction of the background electric field which is directed outwards from Saturn. This current would be drawn from Saturn’s ionosphere along the Alfvén wings on the side facing Saturn. The current exits the interaction region through the Alfvén wings on the side opposite to Saturn. The computational Alfvén wings are composed of 180 “infinite” length line-segments (90 in northern and 90 in southern hemisphere) each of which originates from the pick up region and extends infinitely to the Saturnian ionosphere along the two characteristics given by

\[
\mathbf{V}_A = \mathbf{V}_0 + \mathbf{B}_0 / \sqrt{\mu_0 \rho}
\]

where \( \mathbf{V}_0 \) is the flow velocity, \( \mathbf{B}_0 \) is the background vector field, and \( \rho \) is the plasma mass density.

[16] In accordance with the two-dimensional electric dipole model of Alfvén wing introduced by Neubauer [1980], the Alfvén-wing current is assumed to be proportional to \( \sin(\phi) \) where the azimuthal angle \( \phi \) is measured from the Enceladus-Saturn line (see Figure 9). Current continuity requires that the azimuthal current around the circumference of the obstacle should be proportional to \( \cos(\phi) \). This means that the Alfvénic segments closest to Saturn supply the most current to the pick up region, and the Alfvénic segments farthest from Saturn draw the most current from it. The pick up region is composed of three circular annuli (each subdivided in \( \phi \) into 90 linear segments of length \( 4^\circ \times R \times \pi/180 \)) where \( R \) is the radius of the annulus) spread around the pick up region. The magnetic field from each of the segments is calculated along the spacecraft trajectory from the integrated form of Biot-Savart equation:

\[
\mathbf{B} = \frac{\mu_0 I}{4\pi \rho} \left( \sin \theta_2 - \sin \theta_1 \right)
\]

where \( I \) is the strength of the current flowing through the segment, \( \rho \) is the normal distance of the measurement point from the segment, and \( \theta_1 \) and \( \theta_2 \) are the angles made by the two ends of the segments to a vector normal to the segment that passes through the measurement point.

[17] In the equatorial plane of the mass-loading region, the magnetic perturbations from the currents flowing along the two Alfvén wings are opposite in sign and therefore approximately cancel each other’s effect. In this plane, the magnetic field signature is produced mainly by the current closing through the pick up region of Enceladus. This component of the magnetic field enhances the strength of the magnetic field upstream of the pick up region and reduces it in the downstream direction.

[18] Neubauer [1980] showed that the current flowing through each of the Alfvén wings is limited by the Alfvén conductance \( \sum A_i \approx 1/\mu_0 V_A \) of the medium. This limit is approached when the combined conductance from Pedersen and plasma pick up conductance of the obstacle exceeds the Alfvén conductance of the plasma. In this limit, the total current flowing through each of the Alfvén wings cannot exceed \( I_{\text{max}} = 2\Phi \sum A_i \), where \( \Phi \) is the total electrical potential across the obstacle in the unperturbed flow. Thus \( I_{\text{max}} = 4V_0(R_0) / \sqrt{\rho/\mu_0} \) where \( R_0 \) is the radius of the obstacle, and \( V_0 \) is the ambient plasma speed. In our model, we use the total current flowing through the system as a free parameter, and the only restriction placed on it is that \( I_{\text{max}} \leq I_{\text{max}} \).

[19] We present the modeling results for the three flybys in Figures 10a–10c. We used \( I = I_{\text{max}} = 1.5 \times 10^4 \, \text{Amp} \) for each of the Alfvén wings (for a total of \( 3 \times 10^4 \, \text{Amp} \) flowing through the plasma pick up region) corresponding to an ion density of 60 particles/cm\(^3\) and an ion mass of 17 amu. For E3 flyby, the model reproduces the phasings of
the signature correctly, but the spatial extent and the strength of the model components are underdetermined even with the maximum permissible current strength. For E4 and E11 flybys, even the signs of the $B_x$ and $B_y$ components do not match the model results. These two flybys suggest that the center of the obstacle must lie much below Enceladus as illustrated in Figure 11 for a plume source.

[20] Based on these findings, the effective size and the location of the source were treated as additional fit parameters. The model of the current system used to calculate the magnetic field for the displaced source is illustrated in Figure 12. The resulting best fits for the three flybys are shown in Figures 13a–13c. The required size of the source and the shift required for the source location are displayed in the titles of the figures. For E4 and E11 flybys, we were able to get solutions with a source size of $\sim 3 R_E$. However, for the E3 flyby, both the source size and its location had to be changed significantly from the E4 and E11 values. It can be seen that the fits have improved considerably and reproduce the phasings of the signatures correctly. The RMS differences between the data and the best fit models for E3, E4, and E11 flybys are 0.6, 0.7, and 1.8 nT, respectively. Because the scale size of the obstacle is much larger than Enceladus, the Alfvén wing currents do not intersect Enceladus directly and therefore are not affected by the exosphere of Enceladus. Further improvements to the fits would require better characterization of source cloud boundaries and self-consistent ionization rates throughout the pickup region. Such an undertaking is beyond the capability of the simple Biot-Savart model used here. The discrepancy in fitting the $B_y$ components for both E4 and E11 suggests that in addition to the primary molecular source of gas from the plume, another secondary but more extended source of plasma – which is displaced in the $y$ direction from the primary source – may exist in the environment of Enceladus. It is likely that this additional source results from the slow break-up and ionization of the dust particles recently injected into complex paths around Saturn’s orbit (see http://saturn.jpl.nasa.gov/multimedia/images/image-details.cfm?imageID=2276).

[21] In order to understand the sensitivity of the model to the fit parameters, in Figure 14, we switched the parameters
used for the E4 and E11 fits with those of E3 and vice versa. It can be seen that the fits have deteriorated considerably. The RMS differences between the data and the switched parameter models are now 0.9, 2.1, and 6.8 nT for E3, E4 and E11 flybys, respectively.

We infer that Cassini remained outside the current carrying regions illustrated in Figure 12 from the fact that no sharp field rotations usually associated with crossings into current sheets were observed in the three data sets. Therefore we believe that even though the best fits to the data shown in Figures 13 are not perfect, the computed source size and current strength are meaningful because only an integrated response to the currents was observed in the data. The inferred current strengths can then be used to place limits on the total pick up of mass near Enceladus as we show next.

As shown by Goertz [1980], the pick up current density \( J_y \) is related to the plasma pick up rate \( \dot{n} \) through the relation:

\[
J_y = q \dot{n} r_L = \dot{n} m v_\perp B
\]

where \( r_L \) is the gyroradius of the newly picked up ion, and \( q \) is the charge of an electron, \( m \) is the mass of the ion, and \( v_\perp \) is the velocity of the picked up ion in the moon’s rest frame. Integrating the equation over the surface area through which the currents are flowing, we get the total current

\[
I_y = \int \int J_y dYdZ = \frac{M v_\perp}{B L_y}
\]

where \( M = \iiint \dot{n} dYdZ \) is the mass-loading rate in kg/s, and we have assumed a uniform pick up rate over the \( y \) coordinate, and \( L_y \) is the dimension of the source in the \( y \) direction. The above equation can be rearranged as:

\[
M = \frac{B L_y I_y}{v_\perp}
\]

Using a field strength of 320 nT, a source diameter of 6–10 \( R_E \) and the modeled total current of \( 0.3 \times 10^5 \) to \( 0.9 \times 10^5 \) Amp yields a mass-loading rate of \( \sim 0.6–2.8 \) kg/s. Here we assumed that all of the ions were picked up at the full corotation velocity of 26 km/s. Equation (5) shows that for lower pick up velocities, the mass-loading rate would be higher for the same amount of current flowing through the system. Lower pick up velocities result when the Alfvén conductance of the magnetosphere is not sufficient to carry the currents required for pick up at full corotation velocity. This situation is reached when the current in each of the Alfvén wings is close to \( I_{\text{max}} \) (the Neubauer limit). The modeled current however is always between 20 and 60\% of \( I_{\text{max}} \), suggesting that the Alfvén conductance can support pick up at full corotation velocity and that the mass-loading rate of \( \sim 1–3 \) kg/s is realistic. This finding has a direct bearing on the length of the plasma wake. When the plasma is picked up at speeds much lower than the corotation speed, a long wake forms behind the moon (as for example at Io) where the plasma is brought to the full corotation speed. However, because we believe that plasma in Enceladus’ plume was picked up at close to the corotation speed, we expect that only a short wake would form behind Enceladus.

5. Discussion and Conclusion

Recently, Pontius and Hill [2006] have analyzed plasma velocity data from the Cassini Plasma Spectrometer (CAPS) instrument from the E11 flyby to place constraints on the plasma pick up occurring in the vicinity of Enceladus. By using an analytic model of electrodynamic coupling between Enceladus and the ionosphere of Saturn, they were able to relate the plasma velocity in the neighborhood of Enceladus to the plasma pick up rates. To explain the
observed plasma velocity perturbation, Pontius and Hill require a total mass-loading rate of \(>100\) kg/s in the immediate vicinity of Enceladus. Their estimate is a factor of \(~50\) higher than the estimate derived by us from modeling the observed magnetic field data. Though some of the differences in the two estimates of mass-loading rates may have resulted from the differences in the two approaches used to describe the electrodynamic interaction, we believe that the main difference in the two results stems from the vastly different scale sizes of the obstacles derived from the two data sets. Our data set for E11 is consistent with a source size with a radius of \(~4\) \(R_E\), whereas the velocity data used by Pontius and Hill indicate that the perturbations occurred over a radius of \(~30\) \(R_E\). Equation (5) shows that if the plasma pick up occurs at roughly the full upstream velocity, the total mass-loading rate is proportional to the square of the source size. Thus, if the source is 7 times larger than that inferred from our work, it would mass-load plasma at a rate of 49 times, \(~100\) kg/s, similar to the estimate of Pontius and Hill.

More recently, Burger et al. [2007] have developed a three-dimensional Monte Carlo neutral cloud model of the Enceladus plume to simultaneously model the INMS water-vapor density profile along Cassini’s trajectory and the UVIS measurements of the column density of the plume. They show that the observations are consistent with a two-component source model of water. They require a distributed global neutral component with a source rate of \(8 \times 10^{25}\) \(\text{H}_2\text{O}/\text{s}\) (2.4 kg/s) and a plume source from the southern regions with a neutral source rate of \(10^{28}\) \(\text{H}_2\text{O}/\text{s}\) (300 kg/s). Further by using the latest estimates of ionization and charge exchange reaction rates, Burger et al. calculate that out of this \(~300\) kg/s neutral source rate, the amount that gets picked up by the plasma (that is ionized, mainly through charge exchange) in the vicinity of Enceladus is between 1.5 and 3 kg/s, an estimate that is very close to our estimate of \(~0.6\) to \(~2.8\) kg/s.

Finally, a lack of significant enhancement of wave power in the ion cyclotron waves during the three flybys is consistent with the region of plasma pick up being downstream of the trajectories. This is easily understandable if the source is only a few Enceladus radii in size and is displaced slightly in the direction of the flow. If the source radius were \(~30\) \(R_E\), as required by the model of Pontius and Hill [2006], Cassini would have traveled right through the strong pick up region and should
have observed strong ion cyclotron ion cyclotron waves. Thus, the ion cyclotron ion cyclotron wave data are also inconsistent with the model results of Pontius and Hill.

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References

Figures

**Figure 14.** Magnetic field data obtained during the three flybys of Enceladus (solid) and the model field (dashed) using fit parameters for the E4 and E11 flybys that were previously used for the E3 model in Figure 13 and using parameters for the E3 flyby that were previously used for the E11 model in Figure 13. These fits with switched parameters produce visibly poorer fits than those obtained from our best fit models shown in Figure 13. The used fit parameters are indicated in the title of each of the three subfigures.


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