Determining ion production rates near Saturn’s extended neutral cloud from ion cyclotron wave amplitudes


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Recent Cassini observations of active venting of water molecules from Enceladus indicate that the moon is the primary source of Saturn’s extended neutral cloud. Ionization of the neutrals through charge exchange creates a population of newborn ions with a velocity space distribution, which is highly unstable to the generation of electromagnetic ion cyclotron waves. Cassini observed such ion cyclotron waves, finding spatial and temporal variability in the wave amplitudes throughout the extended neutral cloud region. Since the amount of energy in the ion cyclotron waves is proportional to the number of newborn ions generating them, it is possible to infer the ion production rate in the region. To do so, we use two-dimensional electromagnetic hybrid (kinetic ions, fluid electrons) simulations to investigate the growth and nonlinear evolution of ion cyclotron waves. We focus on conditions near Enceladus’ L shell and compare the simulated and observed ion cyclotron wave amplitudes to estimate the neutral densities and ion production rates. Our simulation results find a relatively linear relation between ion production rate and quasisteady wave energy level ($\delta B^2$). For conditions near Enceladus’ L shell, we find that water group ion production rates of 0.007–0.014/cc/s (which yield wave amplitudes of $\sim$0.1–0.3 nT) are appropriate. For ion production within an annulus volume from 3.9 to 4 $R_S$, we obtain ion production rates of $3.8 \times 10^{26}$ to $7.6 \times 10^{26}$ ions/s or 10.2–20.4 kg/s.


1. Introduction

When the Cassini spacecraft passed through the region between ~3.5–6.5 $R_S$, the magnetometer detected left-hand polarized electromagnetic plasma waves primarily near the gyrofrequencies of water group ions (Figure 1). These have been identified as ion cyclotron waves, generated by populations of newborn ions originating from the extended neutral cloud which encircles Saturn and is sourced by the moon Enceladus orbiting at 3.95 $R_S$ [Leisner et al., 2006]. When particles in the neutral cloud are ionized, they are accelerated in the perpendicular direction by the saturnian corotation electric field (i.e., they are “picked up”), forming a ring distribution in velocity space (Figure 2). This anisotropic distribution is unstable to the generation of left-hand electromagnetic waves with frequencies below the local ion gyrofrequency. As the waves are generated, the newborn ion ring scatters to a more isotropic distribution, and over time becomes like the background plasma.

Linear dispersion analysis indicates that the growth rate of the ion cyclotron waves is dependent on the plasma and mass loading conditions [Leisner et al., 2006; Cowee et al., 2006]. As such, the characteristics of the waves, for example, their amplitude, provides a diagnostic of the conditions in the extended neutral cloud. The wave amplitude is generally determined by the number of newborn ions, their kinetic energy, and the fraction of that kinetic energy that is lost to the waves during the scattering process. At most, the ions will lose 50% of their initial energy to the ion cyclotron waves [Huddleston et al., 1997]. The initial energy of the newborn ion is determined by the difference in the velocity it had as a neutral right before it is ionized and the velocity to which it is accelerated, that of the corotating background plasma. It is reasonable to assume that the newborn ions at a given radial distance from Saturn all have similar initial energies (i.e., the ring velocity distribution is relatively narrowly defined in velocity space). Wave amplitude, then, is proportional to the newborn ion density, and variations in the wave amplitudes over space and time can be indicative of variable mass loading conditions.

Figure 3 shows the median (solid line) and upper and lower quartiles (dashed lines) of equatorial ion cyclotron wave amplitudes versus radial distance observed by Cassini...
on all passes across the region between \( \sim 4 \) and \( 6 \) \( R_S \), binned every 0.1 \( R_S \) (J. S. Leisner, manuscript in preparation). Ion cyclotron waves were observed at all azimuths around Saturn, regardless of the location of Enceladus. Because Enceladus is a source of new material for the extended neutral cloud, the ion cyclotron waves observed at Enceladus’ L shell when the moon is adjacent to the spacecraft are much higher amplitude than those observed when the moon is far from the spacecraft. As such, data obtained near the moon is excluded from Figure 3, to prevent biasing of the wave amplitudes toward higher values. There are large orbit-to-orbit variations as shown by the dots on Figure 3, which indicate the average wave amplitudes on each Cassini orbital leg, binned every 0.1 \( R_S \). For example, the average wave amplitudes on the orbital legs in the bin between 3.9 and 4 \( R_S \) (shaded region in Figure 12) vary from \( \sim 0.10 \) to 0.46 nT. Near Enceladus, itself, the generated waves were observed to reach amplitudes of \( \sim 1.5 \) nT (J. S. Leisner, personal communication, 2008). Because higher densities of newborn ions generate higher wave amplitudes, we may expect that the variations in wave amplitudes near the Enceladus L shell between Cassini orbital legs are indicative of variation in local mass loading rate. Additionally, the median wave amplitudes (solid line) are highest between 4 and 4.5 \( R_S \) and then generally decrease with distance, which suggests a stronger source of pickup ions near Enceladus’ L shell [Leisner et al., 2006]. It is important to note that Figure 3 shows wave observations only in the equatorial plane (i.e., within 0.05 \( R_S \)). Even though ion cyclotron waves were observed propagating as far as \( \sim 0.5 \) \( R_S \) off the equatorial plane, they do not directly represent local ion production because these off-equatorial plane wave amplitudes are also representative of waves which were generated at the equatorial plane and have propagated away along field lines [Leisner et al., 2007]. We emphasize, therefore that the results presented in this manuscript focus only on the conditions near Enceladus’ L shell in the equatorial plane and are not directly applicable to other radial distances or other latitudes where the different background plasma and ion pickup conditions will yield a different relationship between wave amplitude and ion production rate.

**Figure 1.** Time series of ion cyclotron waves observed by Cassini near Enceladus on 26 June 2005. Data are shown in magnetic field-aligned coordinates, wherein \( B_c \) is inward radial direction, \( B_a \) is the azimuthal direction, and \( B_b \) is the magnetic field direction (through the courtesy of J.S. Leisner).

**Figure 2.** Cartoon of the ion pickup process near Enceladus [adapted from Huddleston et al., 1998].
While linear dispersion analysis can predict how the growth rate of the instability varies under different conditions, it cannot tell what the wave amplitudes will be. Therefore in order to better understand the relationship between the wave amplitudes and mass loading conditions, we use a hybrid simulation technique to self-consistently model the necessary nonlinear wave-particle interactions. To begin our study, we first show results which compare the simulated waves to linear dispersion theory predictions, so that we may verify that the simulation can be applied to this problem. After that, we show simulation results which model the creation of newborn ions via the dominant ionization mechanism of charge exchange [Tokar et al., 2006], which will allow us to relate ion production rates, \( \Lambda \), to steady state wave amplitudes, \( B_{\text{eq}} \), that are generated by the newborn ions. We then apply our simulation results to the observed wave amplitudes near Enceladus’ L shell, and infer ion production rates there.

This paper is organized as follows: section 2 describes the hybrid simulation technique and our choice of simulation parameters; section 3 discusses the comparison between the simulation results and linear theory (sections 3.1 and 3.2), the results of the simulation for varying ion production rate (section 3.3), and our inferred ion production rates and neutral densities near Enceladus (section 3.4); section 4 summarizes the important results and discusses future applications of this technique.

2. Methodology

We use a 2.5-dimensional hybrid simulation technique which considers particle position in 2 dimensions \((x, y)\) and particle velocities and fields in all 3 dimensions. Ions are treated kinetically while electrons are treated as an inertialess fluid [e.g., Winske et al., 2003; Omidi et al., 2005]. Periodic boundary conditions are used. The ambient magnetic field, \( B_0 \), is uniform throughout the simulation box and is aligned with the \( y \) axis, while the corotation direction is along the \( x \) axis. For this study, we first perform simulations to be compared with linear theory, and then perform simulations to test the dependence of ICW amplitude on ion production rate. For comparison with linear theory, we use the following simulation parameters: the ambient magnetic field is \( B_0 = 325 \, \text{nT} \), with total ion density of \( n_0 = 45 \, \text{ions/cc} \), and all ions are \( \text{O}^+ \) (water group) which have mass \( m_0/m_p = 16 \) and charge \( q_0/q_p = 1 \). Normalization parameters are Alfvén speed \( v_A = B_0/\sqrt{\mu_0 n_0 m_0} = 264 \, \text{km/s} \), inertial length \( c/v_A \approx c/\rho e_0 n_0 e_2 = 135 \, \text{km} \), and gyrofrequency \( \Omega_i = q_0 B_0/m_0 = 0.31 \, \text{Hz} \). These parameters are based off Tokar et al. [2008] and are not meant to be strictly representative of the conditions near Enceladus’ L shell, but are chosen for the purposes of comparing simulation results and linear theory predictions. Results from the injection simulations are discussed using these same normalization parameters for simplicity. For all runs, the simulation box is \( 16 \, c/\nu_A \) with 128 gridcells in both the \( x \) and \( y \) directions and the timestep is \( 0.025 \, \Omega_i \).

For the first simulation results we show, which we compare with linear theory, the simulations are all initial-value runs. This means that all the ring ions are present at the start of the simulation and there is no creation of newborn ions during the run. The second set of simulation results we show involves newborn ion creation via charge
exchange. Since we consider the behavior of ions in our simulated system but not the neutrals, the energy of the system is continuously increasing as newborn ion energy is injected but since we create new ions from old ions, the mass is conserved. While the continuous creation of newborn ions is a more realistic treatment of ion pickup conditions in the extended neutral cloud region, it is important that we begin our study of the instability using simulations in which energy is conserved over time, where we are sure we can compare simulated results to linear theory. After doing that, we can carry out simulations where newborn ions are continuously created, to see the nonlinear effects that the injection of free energy into the system has on the generated waves.

The simulation parameters used for comparison with linear theory are given in Table 1. The plasma is initialized with a newborn ion ring component and a maxwellian core component. The ring is given nearly zero temperature in the parallel direction and a perpendicular pickup velocity of 26.4 km/s (58.3 eV) and has a density of 22.5 ions/cc. The core is given a temperature of 29.15 eV and has a density of 22.5 ions/cc. Temperatures are based off Tokar et al. [2008] while the relative densities of the ring and core component are arbitrarily chosen for the purposes of comparing simulation results with linear theory.

The simulation parameters used for studying the effects of variable ion production rate are given in Table 2. To model ionization by charge exchange during the run, simulation particles are randomly selected and suddenly given a perpendicular velocity of 26.4 km/s and parallel velocity of zero as if they were newborn ions. This has the same effect of charge exchange, of removing background ions and replacing them with newborn ions, while the total ion density remains the same. We define the ion production rate, $\Lambda$, as uniform and continuous during a given run, but we vary it between runs to see the effect.

To compare the simulation results with linear theory, we use the simulated plasma conditions as inputs to the dispersion solvers of Huddleston et al. [1997] and Ronmark [1982]. In the past, the Huddleston et al. [1997] dispersion solver has been successfully used to compare linear theory predictions and hybrid simulations of ion cyclotron waves generated near Jupiter’s moon, Io [Cowee et al., 2006]. The dispersion solver considers ring velocity distributions rather than bimaxwellian velocity distributions, which is more appropriate for conditions in Saturn’s extended neutral cloud region. Comparing simulated waves with those predicted by linear dispersion theory is an important check of the validity of the simulation results, and therefore an important first step in our analysis.

3. Results
3.1. Initial Value Simulations

To begin our study of the growth of ion cyclotron waves for conditions in the extended neutral cloud region, we carry out initial-value simulations for the parameters listed in Table 1. A time history of the simulated (1) fluctuating magnetic field energy density, (2) ring velocity, (3) ring parallel temperature (gray line) and perpendicular temperature spread (black line), and (4) core parallel (gray line) and perpendicular (black line) temperatures.

![Figure 4. Time history of simulated quantities for initial-value simulation.](image)

### Table 1. Simulation Input Parameters for Comparison With Linear Theory

<table>
<thead>
<tr>
<th>$j$</th>
<th>$m_i$ ($m_p$)</th>
<th>$\lambda_r$ (cc/cc)</th>
<th>$T_\parallel$ (eV)</th>
<th>$T_\perp$ (eV)</th>
<th>$v_r$ (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring</td>
<td>16</td>
<td>22.5</td>
<td>$\sim 0$</td>
<td>$\sim 0$</td>
<td>26.4</td>
</tr>
<tr>
<td>Core</td>
<td>16</td>
<td>22.5</td>
<td>29.15</td>
<td>29.15</td>
<td>-</td>
</tr>
</tbody>
</table>

$B_0 = 325$ nT, $n_0 = 45$ ions/cc, $v_T = 264$ km/s, $c/\omega_p = 135$ km, $\Omega_i = 0.31$ Hz.

![Table 2. Simulation Input Parameters for Variable Ion Production Rate Study](image)
the ring stops near the time of saturation, the ring does continue to lose energy after saturation as evidenced by the gradual decrease in \(v\) during the instability decay phase. As such, the ring still provides energy to the waves during the decay phase when energy is being transferred to the core, so the wave decay shown in Figure 4a is gradual. The anisotropy of the ring component at \(\Omega t = 70\) is around 50, and by the end of the run at \(\Omega t = 2000\) has asymptoted to a value near 25. Thus even though the ring loses a substantial amount of energy in the process of scattering, it does not scatter to a fully isotropic state. The core component is also important in the behavior of the instability as it damps wave growth and becomes heated (Figure 4d). By \(\Omega t = 170\), the core component anisotropy is about 1.1, and by the end of the run at \(\Omega t = 2000\) it has asymptoted to about 1.2. The transfer of ring free energy to the core component is an important way that the instability can reduce free energy instead of losing it to wave growth [e.g., Cowee et al., 2007].

[13] Power spectral density of the generated waves during \(\Omega t = 75–177\) is shown in Figure 5. The left panel shows compressional waves at perpendicular propagation, the middle panel shows the Bz transverse waves at parallel propagation, and the right panel shows the Bx transverse waves at parallel propagation. Peak power is in parallel-propagating transverse waves with frequency just below \(O^+\) gyrofrequency (solid gray line). Weaker power near the \(O^+\) gyroharmonics (dotted gray lines) is seen in the compressional waves at perpendicular propagation. Peak power is at the \(n = 2\) harmonic and decreases with each successively higher harmonic. We do not show the compressional waves at parallel propagation or the transverse waves at perpendicular propagation because their power is orders of magnitude lower than what is shown in Figure 5. The wave modes present can be identified by looking at the \(\omega - k\) spectrum (Figure 6). The wave mode shown in the middle and right panels has power at the ion gyrofrequency extending over \(2 < k c / \omega_{pi} \approx 8\), while the wave mode in the left panel has power at twice the ion gyrofrequency extending over \(1 < k c / \omega_{pi} \approx 4\). The dispersion of the former mode is that of the ion cyclotron wave, and its dominance at parallel propagation confirms expectations. The latter mode with perpendicular propagation could be
the ion Bernstein wave or harmonic waves excited by the fast magnetosonic mode.

The presence of wave power at harmonics is unexpected because it was not seen at first in the Cassini magnetometer data analysis. Later inspection of the data revealed the presence of short intervals of weak compressional wave power propagating at oblique (but not perpendicular) angles at the first harmonic of the water group ion gyrofrequency (M. Rodriguez-Martinez, manuscript in preparation). Because the harmonic modes generated in the simulation are much weaker than the fundamental mode, they are perhaps too small to be generally observed in the extended neutral cloud region all the time. Looking at the magnetic fields across the simulation box, harmonic waves are not readily apparent (Figures 7 and 8), though closer examination at oblique angles indicates harmonic ion cyclotron wave power is there (not shown).

3.2. Comparison With Linear Theory

To compare the simulated waves to linear theory predictions, we use the simulated plasma conditions during the growth phase as inputs to the dispersion solver of Huddleston et al. [1997]. Because the ring spreads quickly, the waves generated during the growth phase will have dispersion which is better predicted by a ring which has undergone some spreading (i.e., a warm ring). Thus we do not use the plasma conditions at $t = 0$ (i.e., a cold ring) to predict the generated wave modes, instead we use conditions obtained during the linear growth phase [Cowee et al., 2006]. Figure 9 shows the best fit linear dispersion solutions for the conditions at $\Omega_i t = 100$: Ring $T_{par}$ and $T_{perp}$ are 0.2 and 56.4 eV ($\lambda \sim 280$); Core $T_{par}$ and $T_{perp}$ are 29 and 29 eV ($\lambda \sim 1$). Comparing this to the simulated wave spectrum in Figure 6 (middle and right), there is general agreement between the range of unstable wave numbers ($k_c/\omega_{pi} = 2–10$) and wave number of maximum growth at $k_c/\omega_{pi}/C_{24}^4 = 4–5$. There is disagreement, between the predicted maximum growth rate at parallel propagation, $g_m/\omega_{pi}/C_{24}^0 = 0.037$, and the simulated overall growth rate of 0.026 obtained by fitting a line to the results in Figure 4a. This disagreement is because wave power is distributed at oblique angles and at the cyclotron harmonics, which is not considered in the linear theory prediction.

3.3. Simulations With Ion Production

In the previous section we showed that initial-value two-dimensional hybrid simulations generate waves with properties in agreement with linear theory predictions for conditions in the extended neutral cloud region. In this
section, we carry out the next stage of our study and include continuous ionization in the simulation. For these runs, the simulation is initialized with all core ions (45/cc, 29.15 eV) and then newborn ions are created according to the parameters listed in Table 2. The fluctuating wave energy density over time for the various injection rates, $\Lambda$, is shown in Figure 11. When compared to the instability behavior in the initial-value run (Figure 4a) we see that when ionization is included in the simulation, the instability grows and saturates as usual, but remains at near-saturation levels rather than decaying. The quasisteady wave energy level indicates a relative balance between the energy injected into the waves by newborn ions and the energy removed from the waves due to damping by the plasma. Indeed, this quasisteady wave energy level is proportional to the ion production rate as shown in Figure 12, a result consistent with simulations of mass loading at Jupiter’s moon, Io [Cowee et al., 2008]. For the background magnetic field value used here, $B_0 = 325$ nT, this translates into wave amplitudes of $\sim0.1–1.4$ nT. The waves generated during the run have spectral properties very similar to those seen in the initial-value simulations (e.g., Figures 5 and 6), and so we do not show plots of the waves here. This agreement between the initial-value and ionization simulations indicates that the ionization simulation is a valid technique; even though the ionization simulations include nonlinear effects from the continuous injection of energy, they still generate wave modes which can be predicted by linear theory.

$\gamma/\Omega_0^+$ $k_c/\omega_{pi}$

![Figure 10. Ion Bernstein mode dispersion solutions for the initial-value simulation obtained using the initial plasma conditions in the simulation.](image)

$\langle \delta B/B_0 \rangle^2 = 5.7 \times 10^{-5} \Lambda - 8 \times 10^{-8}$

![Figure 11. Time history of wave energy for the injection runs.](image)

$\langle \delta B/B_0 \rangle^2$ versus injection rate.

Figure 12. Quasisteady wave energy level versus injection rate.

$\Omega_\parallel$ $\Lambda$ (ions/cc/s)

$\langle \delta B/B_0 \rangle^2$ versus injection rate.

![Figure 13. Normalized $v_\perp - v_\parallel$ velocity space density contours of the particles at several times during the run with $\Lambda = 0.014$ ions/cc/s. The velocity distribution is initially isotropic ($\Omega_\parallel t = 0$) and then becomes more anisotropic over time as the population becomes more ring-like, with low parallel velocities and higher perpendicular velocities. Although the ring ions do scatter rapidly over time, they do not scatter to isotropy, and whatever core ions remain at $\Omega_\parallel t = 2000$ have become heated by the generated waves primarily in the perpendicular direction. Thus the quasisteady velocity distribution which develops is anisotropic. This is consistent with Cassini plasma spectrometer observations between 4 and 4.5 $R_S$ which find anisotropic particle distributions [Tokar et al., 2008]. Additionally, our simulated thermalization timescales agree with those of [Tokar et al., 2008].

### 3.4. Ion Production Rates and Neutral Densities

The injection rates of $\Lambda = 0.007$ and 0.014 ions/cc/s in Figure 12 yield maximum wave amplitudes equivalent to $\sim0.1$ nT and 0.3 nT which are the upper and lower quartiles of the distribution of wave amplitudes observed near Enceladus’ L shell (shaded region of Figure 12). We therefore assume that these two $\Lambda$ values indicate an appropriate range of ion production rates in this region. If we presume that the ion production occurs uniformly within an annulus from 3.9 to 4 $R_S$ and with a height of 0.05 $R_S$ above and below the equatorial plane, we obtain ion production rates of $3.8 \times 10^{26}$ to $7.6 \times 10^{26}$ ions/s or 10.2–20.4 kg/s. We do not know if ion cyclotron waves are produced only adjacent to

![Figure 14. Ion Bernstein mode dispersion solutions for the initial-value simulation obtained using the initial plasma conditions in the simulation.](image)
to the equatorial plane (i.e., within 0.05 \( R_S \) height) or over the entire neutral cloud region. As mentioned previously, Cassini observations of the waves above and below the equatorial plane show a structure heavily influenced by the propagation of waves generated at the equator, and is not easily interpreted in terms of local ion production rates [Leisner et al., 2007].

[20] These rates are higher than those of Leisner et al. [2006] who used analytic techniques to estimate ion production rates in the neutral cloud from ion cyclotron wave amplitudes. For their estimate, Leisner et al. [2006] calculated the amount of wave energy propagating away from the equatorial plane divided by the amount of free energy per newborn ion available for wave generation. Since there were assumptions that went into the analysis that would lead to an underestimation of both the energy of the waves and the energy each newborn ion gives to the waves, Leisner et al. [2006] say that their rate of neutral cloud erosion via ionization is likely an underestimate. The authors have since found an error in their original calculation and now give a new erosion rate of \( \sim 2 \times 10^{27} \) ions/s or 55 kg/s for the entire neutral cloud. For the 0.1 \( R_S \) wide annulus from 3.9 to 4 \( R_S \), their calculated neutral cloud erosion rate is \( \sim 1 \times 10^{26} \) ions/s or \( \sim 3 \) kg/s (J. S. Leisner, personal communication, 2008). Our ion production rates are roughly three to seven times higher than this corrected Leisner et al. [2006] value, which is consistent with the presumption that the Leisner et al. [2006] technique underestimates the rates.

[21] Ion production rates also were modeled by [Sittler et al., 2008] by assuming a steady state ion density (based on CAPS data) and dividing that by the loss timescale due to recombination and radial transport. This model did not include charge exchange because it replaces one ion with another and therefore does not change the steady state ion density. As such, their ion production rates and our ion production rates are not directly comparable.

[22] We can attempt to infer the neutral densities at the Enceladus L shell by making several assumptions about the plasma and the charge exchange interactions which are not included in our simulation. The neutral density, \( n_{\text{neut}} \), and the rate of ion production rate via charge exchange, \( \Lambda \), are connected by the charge exchange rate, \( \mu \), as

\[
\Lambda = n_{\text{neut}} \mu
\]  

and

\[
\mu = \sum_j \sigma_j v_r n_{\text{ion},j}
\]

where \( \sigma_j \) is the charge exchange cross section for ion species \( j \), \( v_r \) is the pickup velocity, and \( n_{\text{ion},j} \) is the ion density of species \( j \). \( \sigma_j \) is taken from Table 1 of Burger et al. [1999], \( v_r \) is taken as the nominal pickup velocity of 26 km/s at 4 \( R_S \), and \( \Lambda \) is known from the simulation. The values of \( n_{\text{ion},j} \) for the water group ions are an important variable in this calculation, but are not represented in our simulation. For our purposes, using one species of water group ion to represent all of them was sufficient because the ion cyclotron waves generated by newborn water group ions cannot be distinguished in the magnetometer observations [Leisner et al., 2006]; however, when determining charge exchange reaction rates, the relative densities of the species are important. We therefore make the arbitrary assumption that the 45 ions/cc we simulate is equally divided among \( O^+ \), \( OH^+ \), and \( H_2O^+ \), which are the ion species with charge exchange cross sections listed in Table 1 of Burger et al. [1999]. This table also gives a cross section for reactions between \( H^+ \) and the neutral cloud. We did not include \( H^+ \) in our simulation because it does not significantly affect the ion cyclotron waves generated by the heavier water group ions. For this neutral density calculation, however, it is important to include this reaction. We assume that the \( H^+ \) density is 4 ions/cc which is about 10% of the water group ion density, as is consistent with the relative densities observed by CAPS [Tokar et al., 2008].

[23] For \( \Lambda = 0.007–0.014 \) ions/cc/s our estimated neutral densities are \( 1.4 \times 10^5 \) to \( 2.8 \times 10^5 \) neut/cc. These values
are one to two times higher than the background neutral densities predicted by the Enceladus neutral production model of Burger et al. [1999] for distances away from the moon, itself. If we multiply our neutral densities by twice the height of 0.05 $R_S$ (our equatorial ion cyclotron wave generation region [Leisner et al., 2007]), we obtain toroidal column densities of $8.4 \times 10^{12}$ to $1.7 \times 10^{13}$ neut/cm$^2$, which are in the range of azimuthally averaged column densities modeled by Johnson et al. [2006] for the torus of water group molecules vented from Enceladus. We note, though, that Johnson et al. [2006] give a scale height for this neutral torus of 0.15 $R_S$, three times larger than what we are assuming.

4. Summary and Future Work

[24] We have shown that the two-dimensional hybrid simulation can successfully reproduce the growth of ion cyclotron waves generated by newborn ions for conditions like those in the extended neutral cloud region. The simulated waves have the dispersion characteristics predicted by linear theory and the amplitudes are in the range observed by spacecraft. Simulated wave modes have peak ion cyclotron wave power at wave numbers of $k_{\parallel} c / \omega_{pi} = 4$–5 and frequencies just below $\Omega (v_{th} \sim 70$ km/s). When newborn ions are continuously produced in the simulation, the waves maintain a quasisteady wave energy level over time which is proportional to the ion production rate. For ion production rates between $\Lambda = 0.007$ and 0.014 ions/cc/s, the wave amplitudes are in the typical range (0.1–0.3 nt) observed by the Cassini magnetometer near Enceladus’ L shell but away from the moon, itself (J. S. Leisner, manuscript in preparation).

[25] For an annulus volume from 3.9 to 4 $R_S$ with total height of 0.1 $R_S$, the ion production rates are $3.8 \times 10^{26}$ to $7.6 \times 10^{26}$ ions/cc/s or 10.2–20.4 kg/s. These rates are three to seven times higher than those of Leisner et al. [2006] (corrected values; J. S. Leisner, personal communication, 2008), who determined ion production rates from ion cyclotron wave amplitudes using analytic techniques. That our ion production rates are higher than theirs is reasonable, since Leisner et al. [2006] indicate that their calculations likely yield underestimates of the ion production rate.

[26] We estimated neutral densities from the ion production rates by assuming a certain relative composition of the plasma species and using the charge exchange cross sections given by Burger et al. [1999]. From these assumptions, we estimate the neutral densities at Enceladus’ L shell away from Enceladus are $1.4 \times 10^9$ to $2.8 \times 10^9$ neut/cc. These values are in agreement with the Burger et al. [1999] neutral source model for Enceladus. We note, though, that our estimates are speculative as they do not include comprehensive treatment of the charge exchange reactions, which is beyond the scope of this paper.

[27] At the end of the simulations, the ion velocity distribution is relatively steady in an anisotropic state. This is not only due to the continuous addition of highly anisotropic newborn ions but also because the newborn ion population does not scatter to isotropy in the process of generating waves, and because the background ion population is heated by the generated waves to an anisotropic state. This also agrees with Cassini plasma spectrometer observations which saw anisotropic plasmas between 4 and 4.5 $R_S$ [Tokar et al., 2008].

[28] The results we show in this paper are only appropriate for conditions near Enceladus’ L shell because different plasma and magnetic field conditions at other radial distances will yield a different relationship between simulated ion production rate and wave amplitude. In a later paper, we will use our viable technique to consider a range of distances within the extended neutral cloud region to infer radial mass loading and neutral density profiles. Additionally, we hope to simulate the conditions necessary for mirror mode wave growth as was observed beyond ~6 $R_J$ [Russell et al., 2006]. Mirror mode waves and ion cyclotron waves are driven by the temperature anisotropy of pickup ions yet their growth rates depend on the plasma conditions, most notably the plasma beta. With increasing beta at larger radial distances, mirror mode waves begin to grow in addition to the ion cyclotron waves and eventually dominate the wave spectrum (J. S. Leisner, manuscript in preparation).

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