



First whistler observed in the magnetosphere of Saturn

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[1] This paper describes and analyzes the first whistler observed in the magnetosphere of Saturn. The whistler was detected by the Radio and Plasma Wave Science (RPWS) instrument on the Cassini spacecraft during the inbound pass on October 28, 2004, at a radial distance of 6.18 R_S (Saturn radii). Based on the measured dispersion, a travel time computation shows that the whistler originated from lightning in the northern hemisphere of Saturn. Using a simple centrifugal potential model for the plasma distribution along the magnetic field line, we have determined the scale height and fractional concentrations of water group ions and protons that give the best fit to the observed dispersion. In addition, a more complex diffusive equilibrium model was also analyzed. The inferred electron density profiles for the two models are very similar. Representative scale heights and equatorial ion fractional concentrations that provided good fits to the dispersion of the whistler were found to be $H_{W^+} = 0.89 R_S$ and $\alpha_{W^+} = 0.7$ for water group ions, and $H_{H^+} = 2.67 R_S$ and $\alpha_{H^+} = 0.3$ for protons. **Citation:** Akalin, F., D. A. Gurnett, T. F. Averkamp, A. M. Persoon, O. Santolik, W. S. Kurth, and G. B. Hospodarsky (2006), First whistler observed in the magnetosphere of Saturn, *Geophys. Res. Lett.*, 33, L20107, doi:10.1029/2006GL027019.

1. Introduction

[2] Whistlers are audio-frequency electromagnetic waves produced by lightning that propagate along the magnetic field line at frequencies below the electron cyclotron frequency and the electron plasma frequency. Whistlers were first discovered in 1918 by *Barkhausen* [1919] using a rudimentary vacuum tube audio amplifier. Later, *Eckersley* [1935] showed that the arrival time varied inversely as the square root of the frequency. *Storey* [1953] was the first to correctly explain the origin of whistlers. He showed that whistlers propagate along the magnetic field line from one hemisphere to the other in a plasma mode of propagation now called the whistler mode. Whistlers have also been detected at Jupiter [*Scarf et al.*, 1979; *Gurnett et al.*, 1979; *Kurth et al.*, 1985] and at Neptune [*Gurnett et al.*, 1990].

[3] In this paper we report the first detection of a whistler in the magnetosphere of Saturn. This whistler was observed by the Radio and Plasma Wave Science (RPWS) instrument on the Cassini spacecraft, which is in orbit around Saturn. See *Matson et al.* [2002] for a description of the Cassini

spacecraft, and see *Gurnett et al.* [2004] for a description of the RPWS instrument. The whistler occurred at 09:58:53 UT (Universal Time) on October 28, 2004, during the inbound pass of orbit A. At that time the spacecraft was north of the equatorial plane at a latitude of 12.3°, a radial distance of 6.18 R_S (Saturn radii), and a local time of 18.47 hours. A frequency-time spectrogram of the whistler is shown in Figure 1. As can be seen the arrival time of the whistler increases with decreasing frequency. This frequency dependence is called dispersion and is one of the basic characteristics of whistlers.

2. Dispersion Analysis

[4] *Eckersley* [1935] showed that the arrival time of a whistler is given by $t = t_0 + D/\sqrt{f}$, where t is the arrival time at frequency f , and t_0 is the time of the lightning flash. The quantity D is called the dispersion constant. The dispersion constant can be obtained by measuring the arrival time as a function of frequency and plotting $1/\sqrt{f}$ versus t . Such a plot is shown in Figure 2. As can be seen the measured arrival time, t , provides a very good straight line fit to $1/\sqrt{f}$, thereby providing strong evidence that the signal is a whistler. The dispersion constant, which is the inverse of the slope of the best-fit straight line, is $D = 81 \pm 0.5 \text{ Hz}^{1/2}\text{sec}$.

[5] Since whistlers are known to propagate to a good approximation along a magnetic field line [*Storey*, 1953], there are two possible propagation paths, one for a lightning source in the northern hemisphere, and one for a lightning source in the southern hemisphere (Figure 3). As a first step in the analysis the dispersion has been calculated for the two possible propagation paths using the following equation

$$D = (1/2c) \int_{f_p/\sqrt{f_c}}^{\infty} \sqrt{f_c} ds, \quad (1)$$

where the integration is carried out along the magnetic field line from the lightning source to the spacecraft [*Helliwell*, 1965]. The frequency $f_p = 8980 \sqrt{n_e}$ Hz is the electron plasma frequency, where n_e is the electron density in cm^{-3} , and $f_c = 28B$ Hz is the electron cyclotron frequency, where B is the magnetic field strength in nT. Equation (1) is valid for wave frequencies well below both the electron cyclotron frequency and the electron plasma frequency, ($f \ll f_c$) and ($f \ll f_p$), and for frequencies satisfying ($f \ll f_c^2$). For the propagation paths being considered, all three of these conditions are expected to be satisfied near the equatorial plane, which is where most of the dispersion occurs.

[6] To evaluate equation (1) we must have a model for magnetic field strength and the electron density at all points along the magnetic field line. Since the axis of Saturn's dipole magnetic field is aligned within one degree of its

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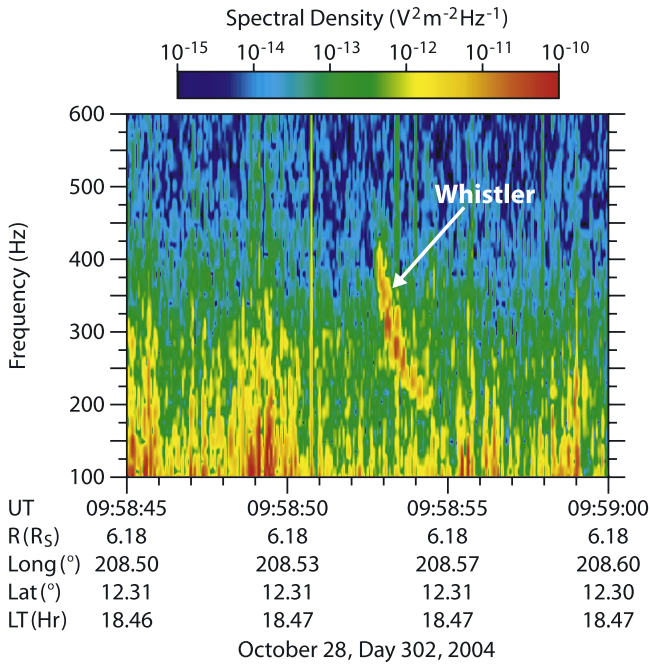


Figure 1. A frequency-time spectrogram of the whistler detected by the Cassini RPWS. The orbital parameters are radial distance in Saturn radii ($R_S = 60,268$ km), latitude and longitude in degrees, and magnetic local time in hours.

rotational axis, it is easy to show that the magnetic field strength at any point along the magnetic field line is given to a good approximation by the equation

$$B = B_0 \sqrt{1 + 3 \sin^2 \lambda} / \cos^6 \lambda, \quad (2)$$

where B_0 is the magnetic field at the equator, and λ is the latitude. From the measured magnetic field at the spacecraft, $B(\text{measured}) = 89.5$ nT at $R = 6.18 R_S$, and the spacecraft latitude, $\lambda = 12.3^\circ$, the constant B_0 in equation (2) can be evaluated and is $B_0 = 73.0$ nT. The *McIlwain* [1961] L -shell value for the magnetic field line, which is the radial distance at which the field line crosses the equator measure in planetary radii, is $L = 6.49$. Since equation (1) must be integrated from the foot of the field line, we must also know the starting latitude for the integration. This latitude, called the invariant latitude, can be found using the equation $\lambda_0 = \cos^{-1}(\sqrt{1/L})$, which for $L = 6.49$ is $\lambda_0 = 66.8^\circ$.

[7] For the electron density in equation (1) we start by using a very simple model for the plasma density. The plasma in Saturn's inner magnetosphere is known to be rotating as though it is rigidly locked to Saturn's magnetic field. This rotation produces a centrifugal force that causes the plasma to accumulate in a disk near the equatorial plane. This disk is called the plasma disk (Figure 3). If the plasma consists of a single species of ions and an equal density of electrons, it is easy to show that the electron number density, n_e , in the plasma disk can be obtained from the following equation,

$$n_e = n_0 \exp \left[-\frac{1}{3} \frac{L^2}{H^2} (1 - \cos^6 \lambda) \right] \quad (3)$$

where n_0 is the number density at the equator, L is the equatorial radius of the magnetic field line in R_S , λ is the

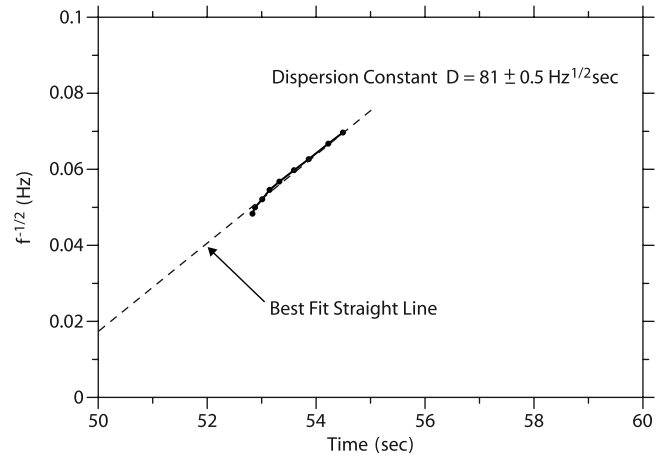


Figure 2. A plot of the inverse of the square root of frequency versus the arrival time for the whistler in Figure 1. The slope of the best fit straight line (dashed) gives $1/D$.

latitude and H is a quantity called the scale height. Equation (3) can be derived from a principle of equilibrium statistical mechanics that states that the density is proportional to $\exp[-W/kT]$ where W is the potential energy, k is Boltzmann's constant and T is an effective plasma temperature. The potential energy is assumed to be entirely due to the centrifugal force, ignoring the gravitational force. The gravitational force is small compared to the centrifugal force beyond about $2 R_S$. The scale height provides a measure of the north-south thickness of the plasma disk, and is given by $H = \sqrt{2kT/3m\Omega^2}$, where m is the ion mass and Ω is the rotation rate of Saturn [Gledhill, 1967; Hill and Michel, 1976].

[8] To see if the observed dispersion can be accounted for by this simple model, the dispersion was computed by integrating equation (1) along the $L = 6.49$ field line using equation (3) for the electron density. The equatorial electron density, n_0 , in equation (3) was determined by requiring that the electron density at the spacecraft ($\lambda = 12.3^\circ$) agree with the electron density, $n_e = 7.5 \text{ cm}^{-3}$, determined from measurements of the local lower hybrid frequency [see Persoon *et al.*, 2005]. Since the scale height, H , in equation (3) cannot be directly measured, this parameter

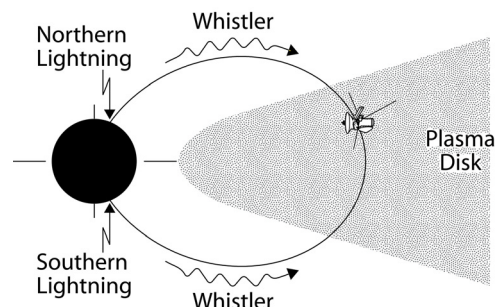


Figure 3. The propagation of a whistler along the magnetic field line. Two lightning sources must be considered, one in the southern hemisphere and one in the northern hemisphere.

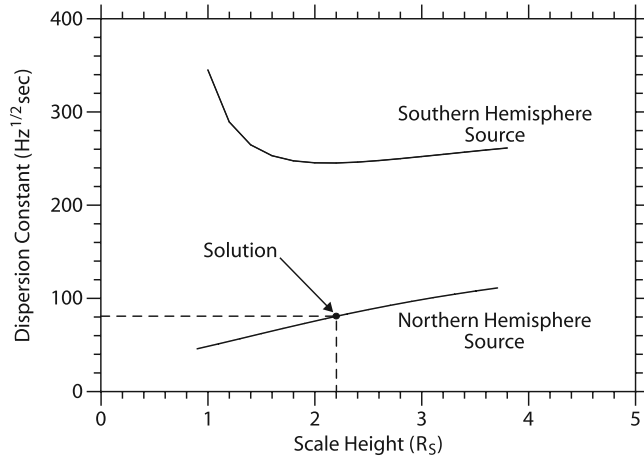


Figure 4. The computed dispersion as a function of scale height for both northern and southern hemisphere sources. The observed dispersion only fits a northern hemisphere source.

was varied until the best fit to the dispersion was obtained. The results are shown in Figure 4. For a southern hemisphere source the computed dispersion is very large, approximately 250 to 350 $\text{Hz}^{1/2} \text{ sec}$, much larger than the observed dispersion, i.e., $D = 81 \text{ Hz}^{1/2} \text{ sec}$. The large dispersion arises because for a southern hemisphere source the whistler must pass through the equatorial plane where the plasma density is very high. For a northern hemisphere source, the computed dispersion is much lower, from about 50 to 100 $\text{Hz}^{1/2} \text{ sec}$, which is comparable to the observed dispersion. The scale height that gives the best fit to the observed dispersion is $H = 2.2 R_S$. Since only a northern hemisphere source matches the observed dispersion, we conclude that the lightning source must have occurred in the northern hemisphere.

3. A Simple Two-Ion Species Model for the Electron Density

[9] Plasma measurements on the Cassini spacecraft [Young *et al.*, 2005] show that the plasma disk consists primarily of water group ions, W^+ , and protons, H^+ . To provide a better model of the plasma density distribution, we have generalized equation (3) to include two ion species

$$n_e = \sum_{i=1}^2 n_i = n_0 \sum_{i=1}^2 \alpha_i \exp\left[-\frac{1}{3} \frac{L^2}{H_i^2} (1 - \cos^6 \lambda)\right], \quad (4)$$

where α_i is the fractional concentration of each species. Because the approximation used in equation (1) always fails at high latitudes where the number density is very small, violating the condition ($f_c \ll f_p^2$), we use the following more general equation for the arrival time

$$t = (1/c) \int \frac{1 + (1/2) \left[\frac{f_p^2 f_c / f (f_c - f)^2}{1 + f_p^2 / f (f_c - f)} \right]}{\left[1 + f_p^2 / f (f_c - f) \right]^{1/2}} ds. \quad (5)$$

This equation is valid for any combination of plasma parameters [Gurnett *et al.*, 1979].

[10] Since there are only two ion species, W^+ and H^+ , that need to be considered, the fractional concentrations must satisfy $\alpha_{H^+} = (1 - \alpha_{W^+})$. Equation (4) then has four unknown parameters, n_0 , α_{H^+} , H_{H^+} , and H_{W^+} . To obtain a solution for these four parameters we need to specify four constraints. One of these constraints is the measured dispersion, $D = 81 \text{ Hz}^{1/2} \text{ sec}$. Two constraints can be placed on the electron density. The first is that the electron density at the equator be $n_0 = 25 \text{ cm}^{-3}$, which is the average value measured by Persoon *et al.* [2005] at $L = 6.49$. The second is obtained from the local upper hybrid resonance frequency at the spacecraft, which gives a local electron density at the spacecraft of $n(\text{spacecraft}) = 7.5 \text{ cm}^{-3}$. Unfortunately, there are no other directly measured constraints, so we must introduce an unknown parameter, which we do by defining a parameter β that is the ratio of the scale height for the protons to the scale height for the water group ions, i.e., $\beta = H_{H^+}/H_{W^+}$. For convenience, we take the ratio of the mass of the water group ions to the mass of the proton to be 16. It then follows from the equation for the scale height (given earlier) that $\beta = 4(T_{H^+}/T_{W^+})^{1/2}$. The best currently available measurements of the ratio of the temperature of the protons to the temperature of the water group ions are from Richardson [1998]. Figure 9 of his paper gives the limits $0.16 \leq T_{H^+}/T_{W^+} \leq 0.5$, corresponding to $1.6 \leq \beta \leq 2.8$. To see if these β values can be accommodated we have obtained best fit solutions for the four unknown parameters, α_{H^+} , H_{H^+} , and H_{W^+} , as a function of β while simultaneously monitoring the mean squared error between the measured arrival times and the arrival times given by equation (5). We have found that a very good fit to the measured dispersion can be obtained for $3 \leq \beta \leq 4$. The representative electron density profiles at the limits of this range, $\beta = 3$ and $\beta = 4$, are shown in Figure 5. For $\beta = 3$ the best fit parameters are $\alpha_{H^+} = 0.30$, $H_{H^+} = 2.67 R_S$, and $H_{W^+} = 0.89 R_S$; and for $\beta = 4$ the best fit parameters are $\alpha_{H^+} = 0.17$, $H_{H^+} = 4.12 R_S$, and $H_{W^+} = 1.03 R_S$. For $\beta < 3$ the mean squared error in the fit increases very rapidly with decreasing β . The reason is that the proton scale height (hence the integrated electron density along the field line) becomes too small to provide the measured dispersion. The best agreement with the

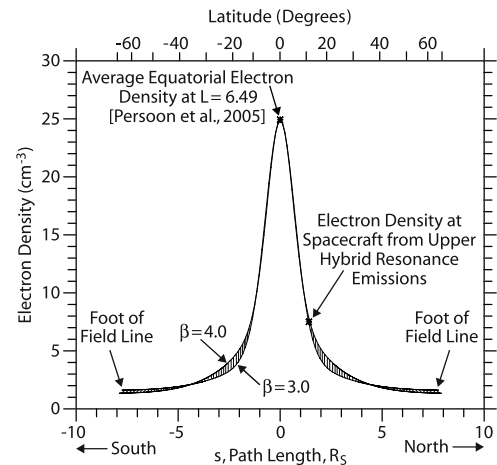


Figure 5. The electron density as a function of path length along the magnetic field line for the simple two-ion centrifugal potential model for $\beta = 3.0$ and 4.0 .

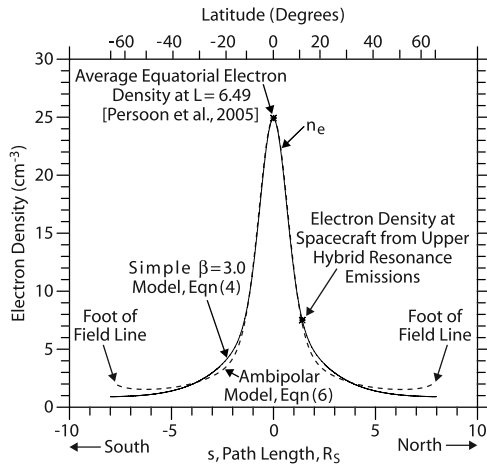


Figure 6. The electron density as a function of path length along the magnetic field line for the best fit ambipolar equilibrium model (dashed line) and for the $\beta = 3.0$ simple two-ion centrifugal potential model (solid line) in Figure 5.

temperatures given by *Richardson* [1998] is for $\beta = 3$, which corresponds to a ratio of the proton temperature to the water group ion temperature of $T_{H^+}/T_{W^+} = 0.5$.

4. An Ambipolar Equilibrium Model

[11] To provide an even more realistic calculation, an ambipolar equilibrium model was used to compute the electron density. In this model, we include the ambipolar electric field force, which was neglected in the previous model. The ambipolar electric field is a consequence of the fact that the electrons have a much larger thermal speed than the ions. In equilibrium, charge neutrality leads to an electric field that keeps the electrons from escaping. As in the previous model we use two ion species, singly charged oxygen ions (i.e., $m_{W^+} = 16$) to represent the water group ions and protons. The plasma density is then calculated using the following equation for each species from *Richardson* [1995, 1998],

$$\frac{\partial P_{i\parallel}}{\partial s} - (P_{i\parallel} - P_{i\perp}) \frac{1}{B} \frac{\partial B}{\partial s} - n_i m_i \frac{\partial}{\partial s} \left(\frac{1}{2} \Omega^2 \rho^2 \right) + n_i \frac{\partial}{\partial s} \left(\frac{GM_S m_i}{r} \right) + n_i q_i \frac{\partial \phi}{\partial s} = 0. \quad (6)$$

The first term is the pressure gradient term, where $P_i = n_i k T_i$ is the pressure. The second term is the magnetic mirror force. The third term gives the centrifugal force, where ρ is the distance from Saturn's rotational axis, Ω is the angular velocity of Saturn, m_i is the mass of i th species, and n_i is the number density of that species. The fourth term is the gravitational force, where G is the gravitational constant, and M_S is the mass of Saturn. The last term is the force caused by the ambipolar electric field, where q_i is the charge, and ϕ is the electrostatic potential.

[12] The three differential equations represented by equation (6), one for each species, together with the charge neutrality condition, $n_e = n_{H^+} + n_{W^+}$, have been solved using

the iterative nonlinear Newton method with the parameters adjusted to give the best fit to the observed dispersion. The constraints used were that the equatorial electron density agree with the results of *Persoon et al.* [2005], i.e., $n_e(\text{equator}) = 25 \text{ cm}^{-3}$, and that the electron density at the spacecraft agree with the value obtained from the upper hybrid resonance frequency, i.e., $n_e(\text{spacecraft}) = 7.5 \text{ cm}^{-3}$. The equatorial proton to water group density ratio was adjusted to give the β value that gave the best agreement ($\beta = 3$) with the results of *Richardson* [1998], as discussed in the previous section. The magnetic mirror force was included in the iteration procedure, but was initially assumed to be zero, i.e., $P_{\parallel} = P_{\perp}$, which seemed like a reasonable first approximation at low to moderate latitude, which is where the largest contribution to the dispersion occurs. The electron temperature, T_e , was fixed at a relatively low value of 1 eV, a value that was found to give good agreement with the model in Section 3.

[13] The fractional concentrations at the equator that give the best fit to the whistler dispersion given the above constraints are found to be $\alpha_{H^+} = 0.17$ and $\alpha_{W^+} = 0.83$. This choice of parameters resulted in proton and ion temperatures of $T_{H^+} = 10.7 \text{ eV}$ and $T_{W^+} = 19.0 \text{ eV}$. A comparison of the electron density profile for these parameters with the $\beta = 3.0$ electron density profile from the simple two-ion model in the previous section is shown in Figure 6. As can be seen the changes in the electron density profile from the simple two-ion model are quite small. The main effects are (1) a reduction of the fractional concentration of protons at the equator, from $\alpha_{H^+} = 0.30$ to 0.17, due to the ambipolar electric field, and (2) an increase in the electron density near the foot of the field line due to the gravitational force. If we increase the electron temperature to more realistic values of $\sim 6 \text{ eV}$ [*Richardson*, 1995], α_{H^+} decreases to 0.05. We have also explored the effects of the magnetic mirror force, i.e., $T_{\perp} > T_{\parallel}$, but a detailed description of these results is out of scope of this paper and will be given elsewhere.

5. Conclusions

[14] This observation of a whistler in Saturn's magnetosphere provides new evidence for the presence of lightning in Saturn's atmosphere. The previous evidence for lightning at Saturn comes from Saturn Electrostatic Discharges (SEDs), which were discovered during the Voyager 1 flyby of Saturn [*Warwick et al.*, 1981]. *Warwick et al.* originally suggested that the SEDs originated from the rings. Later, *Burns et al.* [1983] and *Kaiser et al.* [1984] suggested that SEDs originated from lightning in Saturn's atmosphere. More recently, a cloud feature has been identified in Saturn's atmosphere that is believed to be responsible for SEDs observed by Cassini [*Porco et al.*, 2005; *Gurnett et al.*, 2005]. Optical flashes from lightning have never been observed, even though extensive searches have been conducted.

[15] Although many SEDs have been observed by the Voyager and Cassini spacecraft, there is the question of why only one whistler has been observed so far. The relative scarcity of whistlers is likely due to the very restrictive conditions required for the detection of a whistler. Whereas SEDs, which propagate essentially along a line-of-sight, can

to first-order be detected from a source anywhere on the spacecraft-facing hemisphere of the planet, for a whistler to be detected the lightning must occur near the foot of the field line that passes through the spacecraft. Furthermore, the spacecraft must be relatively close to the planet, well inside of $10 R_S$, otherwise the electron cyclotron frequency would be too small for the whistler to propagate to the spacecraft. The available evidence from SEDs indicates that the lightning at Saturn occurs at relatively low latitudes, typically around 35° , or less. The fact that the lightning responsible for the observed whistler apparently occurred at a higher latitude, around 67° , is surprising. Even more surprising is the fact that it occurred in the northern hemisphere, which for the current tilt of Saturn's rotational axis is in almost complete darkness. This means that the convective activity responsible for the lightning was almost certainly driven by an internal heat source rather than by sunlight. We also looked for an SED at the time when the whistler was observed, but none was found.

[16] In addition to information on lightning, the whistler dispersion gives important constraints on the scale height and composition of the plasma in Saturn's inner magnetosphere, quantities that are difficult to otherwise determine. The dispersion measurements show that, for the best fit two-ion species model, the fractional concentration of water group ions at the equator is about 0.7, with a scale height of about $0.89 R_S$, and the fractional concentration of protons at the equator is about 0.3, with a scale height of about $2.67 R_S$.

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