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Light Ion Concentrations in Jupiter's Inner Magnetosphere

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In this paper, Voyager 1 plasma wave instrument observations of lightning-generated whistlers are combined with Voyager 1 plasma instrument heavy ion ($8 \leq A/Z \leq 64$) charge concentrations to investigate the concentration of light ions ($A/Z < 8$) along the whistler propagation path. Two models for light ion concentration over dipole L shells for L between 5.2 and 6.2 are obtained, one giving a constant concentration along the field line and the other corresponding to an exponential density distribution. Near the equator the light ion concentration ranges from only about 1 to 10% of the heavy ion concentration, while outside of the torus, at distances of from 1 to 1.5 R_J above the equator, the light ions are the dominant species.

INTRODUCTION

During the Voyager 1 flyby of Jupiter in March 1979, the plasma wave instrument observed lightning-generated electromagnetic waves known as whistlers [*Scarf et al.*, 1979; *Gurnett et al.*, 1979], thereby providing evidence for the existence of lightning at Jupiter. Imaging science team photographs of lightning in Jupiter's ionosphere confirmed this conclusion [*Smith et al.*, 1979]. In addition to the implications for atmospheric processes, whistlers can also provide valuable information on the electron concentration along the propagation path from the lightning source to the spacecraft. At earth, whistler observations provided the first remote measurements of magnetospheric electron concentrations [*Storey*, 1953]. Similarly, at Jupiter the Voyager whistler observations have now provided the first measurements of electron concentrations at remote points in Jupiter's inner magnetosphere [*Gurnett et al.*, 1979; *Menietti and Gurnett*, 1980; *Gurnett et al.*, 1981].

In this paper we use whistler dispersion measurements from the plasma wave instrument and heavy ion ($8 \leq A/Z \leq 64$, where A/Z equals the ion mass to charge ratio) plasma concentrations from the plasma instrument (PLS) to investigate the light ion ($A/Z < 8$) distribution in the inner Jovian magnetosphere. The principle used is to add a model light ion distribution to the heavy ion distribution determined from the plasma instrument and adjust the parameters of the light ion distribution until the computed whistler dispersion integrated along the propagation path (assuming charge neutrality) agrees with the observed dispersion. Within the Io torus the heavy ions are the dominant component of the ion density. Consequently, the primary contribution of this paper is the estimate of the light ion concentration near the Io L shell in the region away from the magnetic equator. For a description of the plasma wave and plasma instruments on Voyager, see *Scarf and Gurnett* [1977] and *Bridge et al.*, [1977], respectively.

THEORY

Whistlers observed at the earth by ground-based and satellite instrumentation have been extensively studied and are well understood [e.g., *Helliwell*, 1965]. Primarily due to this understanding, the interpretation of the whistlers observed by Voyager has proceeded rapidly. Herein we use the whistler observations to provide measurements of the plasma concentration integrated along the whistler propagation path, which to a good approximation corresponds to the magnetic field line. Even though this method does not give a local measurement of the plasma concentration, it provides the unique opportunity to investigate regions far removed from the spacecraft trajectory. The Voyager whistler measurements are complementary to the local plasma concentration measurements because they provide information in the region where in situ measurements are not available.

The characteristic frequency-time structure of a whistler, consisting of a decreasing frequency with increasing time, is shown in the spectrogram of Figure 1. Note that all frequencies are within the audible range and would produce a whistling tone if converted to sound. The arrival time t for frequency f follows the approximate law $t = D/\sqrt{f} + t_0$, with D a constant called the dispersion [*Eckersley*, 1935]. The dispersion of the whistler signal is determined by the electron concentation encountered by the wave because the group index of refraction of the whistler mode, n_g, is a function of the electron concentration. To evaluate the dispersion, some simplifying assumptions are necessary.

For purposes of analysis, we assume the whistler propagation paths coincide with magnetic field lines. For the frequencies of interest (1 kHz $\leq f \leq$ 10 kHz) this assumption is supported by ray tracing calculations [*Menietti and Gurnett*, 1980]. Also, even for substantial deviations of the wave vector away from the magnetic field, the group travel time is essentially the same as for field-aligned propagation [*Helliwell*, 1965]. Consequently, we assume field-aligned propagation, in which case n_g is given by the exact expression [*Gurnett et al.*, 1979]

$$n_g = \frac{1 + (1/2)\,[f_p^2 f_g / f(f_g - f)^2]}{[1 + f_p^2/f(f_g - f)]^{1/2}} \tag{1}$$

where f is the wave frequency, f_g is the electron gyrofrequency, and f_p is the electron plasma frequency. At any point in the magnetosphere n_g depends on the magnetic field

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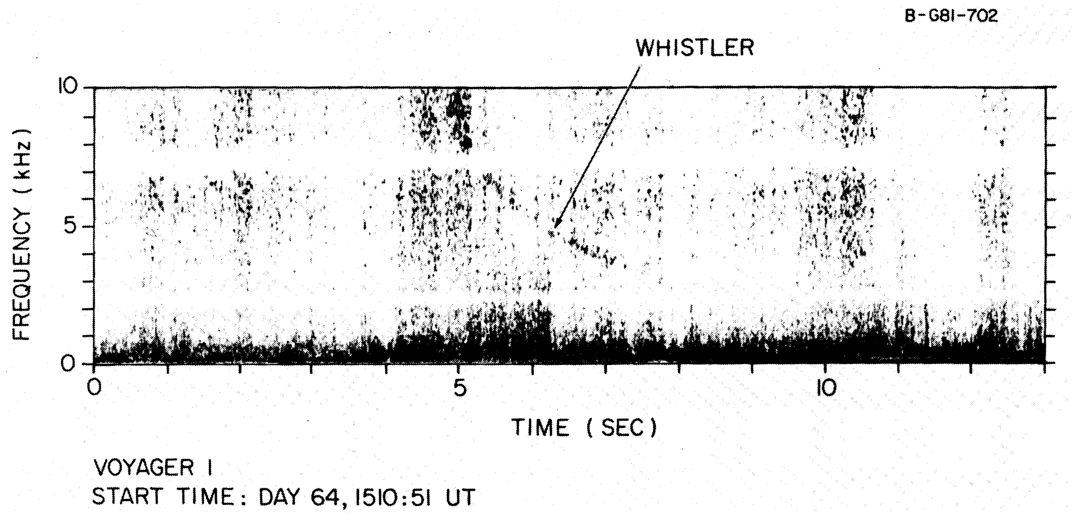

Fig. 1. A representative frequency-time spectrogram of a whistler observed by the plasma wave instrument. By using $t = D/\sqrt{f} + t_0$, D, the dispersion, is found to be 425 s $\mathrm{Hz}^{1/2}$. This is one of the largest dispersions observed and corresponds to travel through a high concentration region of the Io torus.

strength, through f_g, and the electron concentration, through f_p.

In terms of n_g, the arrival time t for frequency f is given by

$$t = (1/c) \int n_g ds \qquad (2)$$

where the integral is evaluated along the magnetic field line connecting the lightning source in Jupiter's ionosphere and the spacecraft. A dipole field is assumed with the magnetic moment adjusted so that the strength at the spacecraft agrees with the measurements made by the Voyager magnetometer team [*Ness et al.,* 1979].

As can be shown [*Gurnett et al.,* 1979], n_g differs appreciably from unity in regions where $ff_g \ll f_p^2$. Since this relation is satisfied throughout the high concentration plasma of the Io torus, we expect the greatest contribution to the whistler dispersion to occur during travel through the torus. The distribution of heavy ions throughout the Io torus has been calculated from the PLS measurements of electron temperature and the concentrations and temperatures of heavy ions [*Bagenal and Sullivan,* 1981]. Essentially all of the whistler observations were obtained in the vicinity of the torus. The measured dispersions show that the electron concentration integrated along the magnetic field line is larger than the values obtained from the heavy ion charge concentrations [*Gurnett et al.,* 1981]. This discrepancy indicates that substantial quantities of light ions are present outside of the torus. The purpose of this paper is to combine the whistler dispersion measurements and the heavy ion measurements from the plasma instrument to determine the light ion concentration outside of the torus.

ION CONCENTRATION MODELS

By using a diffusive equilibrium model for the distribution of a multi-species plasma along dipolar magnetic field lines, the concentrations of heavy ions measured along the spacecraft trajectory have been extrapolated to higher latitudes [*Bagenal and Sullivan,* 1981]. Light ions, with $A/Z < 8$, are not measured as their corotational energy in the inner magnetosphere falls below the energy per charge threshold of the plasma instrument. The concentrations so obtained are shown in the contour map in Figure 2 [from *Bagenal and Sullivan,* 1981]. As shown in this illustration, the plasma is distributed symmetrically about the centrifugal equator. The slight asymmetric appearance of the contours is due to the small angle between the centrifugal and magnetic equators, which varied with the spacecraft longitude over the 7 hour measurement period. In this study the effect of the 10° tilt of the magnetic moment from the rotational axis is assumed to be negligible so that the plasma symmetry surface, or centrifugal equatorial plane, coincides with the rotational and magnetic equatorial planes.

While the concentration of light ions (e.g., H^+, He^+) in Jupiter's inner magnetosphere is largely unknown, there is no a priori reason for doubting their existence. In fact, Jupiter's primarily hyrogen atmosphere has long been proposed as a source of protons. Because we expect the magnetospheric plasma to maintain local charge neutrality, adding the heavy ion charge concentration to the light ion concentration determines the electron concentration. The electron concentration may then be used to calculate the electron plasma frequency ($f_p = 9\sqrt{n}$ kHz, n in cm^{-3}) for use in equation (1). Then, (2) can be used to calculate the

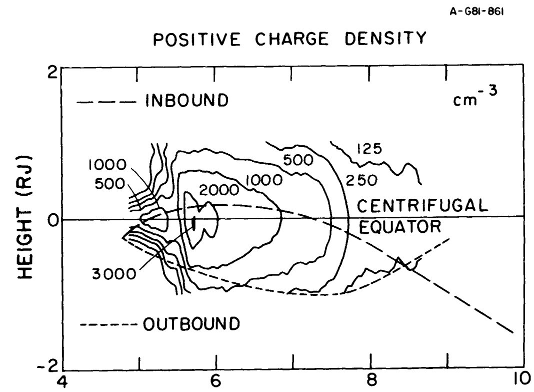

Fig. 2. A contour map of the heavy ion concentration as a function of the radial distance from Jupiter and the height above the centrifugal equator. The map has been constructed from plasma measurements made along the spacecraft trajectory (dotted line) by using a diffusive equilibrium model for the plasma concentration near the equator [from *Bagenal and Sullivan,* 1981].

whistler dispersion for the assumed model of light ion concentration along the whistler propagation path. The parameters of the light ion model can then be adjusted until the calculated dispersion agrees with the observed dispersion.

In this paper we have used two simple light ion models, denoted as the scale height model and the constant density model, which aim to represent two extreme concentration distributions. For the scale height model the light ion concentration, n, is given by

$$n = n_0 \exp - (s/H)^2 \qquad \text{where} \qquad H = \left(\frac{2kT}{3m\omega^2}\right)^{1/2} \tag{3}$$

Here s is the distance above the centrifugal equator along the field line and H, the scale height, is determined by the plasma temperature T; the species mass, m; and the angular rotation rate of Jupiter, ω. To calculate the scale heights, the light ions are taken to be protons at the same temperature as the heavy ions. This temperature ranges from about 10 to 30 eV. Discussions of the scale height model and the problem of the distribution of plasma in Jupiter's magnetosphere can be found in *Gledhill* [1967], *Hill and Michel* [1976], *Siscoe* [1977], and *Bagenal and Sullivan* [1981]. Since the light ion temperature is not precisely known, we include as our second model the high temperature limit of the scale height model. For this model, the constant density model, the light ion concentration is taken as constant along the entire whistler propagation path.

Before presenting the results we demonstrate that in the region exterior to the torus the scale height model is in qualitative agreement with the light ion profile obtained by using the diffusive equilibrium model. Calculations using exact solutions of the diffusive equilibrium model show that the addition of the light ion plasma to the heavy ion plasma has a negligible effect on the resulting heavy ion profile. However, in disagreement with the scale height model, the diffusive equilibrium model predicts that near the equator the light ion concentration will decrease due to the effect of ambipolar electric fields. This effect is exhibited in Figure 3, which shows the heavy ion profile, the light ion scale height and constant density profiles, and the light ion profile obtained by using the diffusive equilibrium model, for the whistler shown in Figure 1. The disagreement between the scale height model and the diffusive equilibrium model is of no great concern for whistler dispersion calculations because near the equator the heavy ions are the dominant species and completely determine the electron concentration in this region. Outside of the heavy ion torus the scale height model provides a very good fit to the light ion distribution given by the diffusive equilibrium model.

OBSERVATIONS AND RESULTS

While the processing of the plasma wave data from the Voyager 1 encounter of Jupiter has not been fully completed, 85 whistlers have already been identified. For a thorough review of the observations, see *Shaw et al.* [1982]. Of these 85 whistlers, 53 were used in this study. The remaining 32 whistlers were omitted because their propagation paths (dipole field lines) lie outside the heavy ion contour map. The 53 whistlers are separated into 14 groups, each consisting of less than 30 s observation time. The reason for the grouping is that frequently several whistlers will occur in rapid succession all having nearly the same dispersion. In these cases the whistlers were considered as a group, since they all correspond to nearly identical propagation paths. For all the whistlers, the dispersion was determined using Eckersley's law, $t = D/\sqrt{f} + t_0$. For each group, an average dispersion ($\bar{D}$) with standard deviation (ΔD) was computed. A standard deviation of zero corresponds to a group with one whistler or to a group containing more than one whistler, all with equal dispersion. The first five columns of Table 1 summarize these observations.

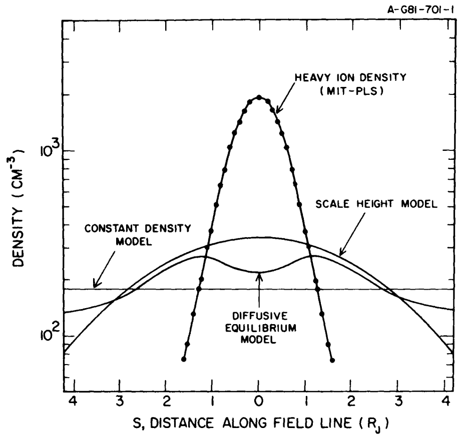

Fig. 3. The light ion scale height and constant density models that, together with the heavy ion concentration, result in an electron distribution along the whistler propagation path (field line) consistent with the frequency-time structure of the whistler in Figure 1. Also shown is the light ion profile obtained by using the diffusive equilibrium model. Outside of the torus the scale height model is in good qualitative agreement with the diffusive equilibrium profile.

For each whistler, the hemisphere of Jupiter from which the signal originated must be determined. We have done this by performing the numerical integration of (2) for the 14 groups assuming no light ions are present. Note that the observed dispersions fall into two categories, large (five cases with $D \sim 250$ s Hz$^{1/2}$) and small (nine cases with $D \sim 100$ s Hz$^{-1/2}$). For the nine small dispersion groups, all observed at northern magnetic latitude, the computed dispersion for a southern hemisphere source is larger than observed. Consequently, these whistlers must have originated in the northern hemisphere since the dispersion is too small for the whistler to have passed through the core of the Io torus. For the five large dispersion groups, a source in the hemisphere that resulted in a propagation path that did not pass through the core of the Io torus yielded such low dispersion that the concentration of light ions necessary to provide the measured dispersion would need to be comparable to or greater than the heavy ion concentration. Therefore, since light ion concentrations this high are in marked disagreement with the concentrations obtained for the small dispersion whistlers, the whistlers observed at northern magnetic latitude originated in the southern hemisphere while the whistlers observed at southern magnetic latitude originated in the northern hemisphere. These results are consistent with previous conclusions [*Gurnett et al.*, 1981].

Figure 4 illustrates the dependance of the numerical integration on light ion concentration for the whistler shown in Figure 1. The solid dots were taken from Figure 1, while the solid curves were calculated by using (2) and the scale height model. Three percentages for the total equatorial concentration contribution of light ions are shown. As is

TABLE 1. Summary of Observations and Results

Day 64, 1979, UT	Number of Whistlers	L Value	Magnetic Latitude, deg.	$\bar{D}$, ΔD (s $\mathrm{Hz}^{1/2}$)	Constant Density Model, n (cm^{-3})	Scale Height Model	
						$H(R_J)$	n_0(cm^{-3})
1006	11	5.37	4.2	71, 8	69	1.5	346
					58		280
					49		230
0957	2	5.45	4.5	83, 0	61	1.6	304
0950	3	5.50	4.7	64, 9	43	1.7	195
					34		146
					26		107
0948	1	5.52	4.8	38, 0	14	1.7	46
0944	1	5.56	4.9	72, 0	72	2.0	112
0940	8	5.59	5.0	48, 6	21	2.1	64
					16		47
					12		42
0937	15	5.62	5.0	61, 12	28	2.1	100
					18		60
					11		30
0935	2	5.64	5.1	69, 12	32	2.1	115
					21		70
					12		40
0931	1	5.68	5.2	72, 0	20	2.6	50
0926	1	5.72	5.3	255, 0	19	2.6	40
0913	4	5.85	5.5	269, 27	51	3.1	110
					23		49
					2		3
1505	1	6.04	−9.1	390, 0	89	3.4	180
1507	2	6.06	−9.1	454, 33	212	3.4	411
					157		307
					109		213
1511	1	6.10	−9.2	425, 0	180	3.5	343

seen, 15% concentration contribution at the equator (n_0 = 343 cm^{-3}) reproduces the observations while 0 and 30% result in too small and too large of a dispersion, respectively. Note that the percentage concentration at the equator refers only to the model used. The actual concentration at the equator is undoubtedly reduced somewhat from these values because of the ambipolar electric fields caused by the heavy ions (see Figure 3). Figure 4 also indictes the approximate sensitivity of this technique to changes in the light ion concentration. As is evident, this method has a precision of a few percent to changes in the integrated light ion concentration.

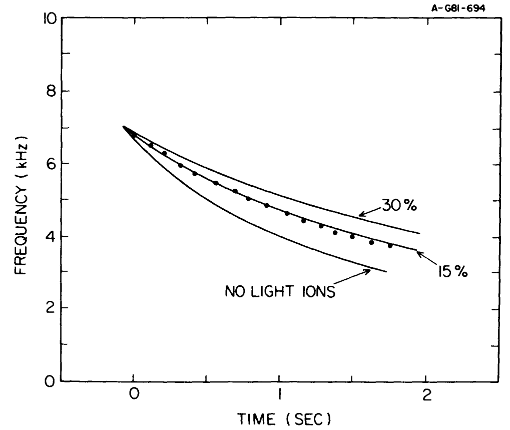

Fig. 4. The solid dots in this frame are taken from the whistler in Figure 1, while the curves were calculated by using equation (2). For the scale height model, 15% density contribution at the equator (n_0 = 343 cm^{-3}) reproduces the observations while 0% (only heavy ions) and 30% result in too small and too large a dispersion, respectively. Note that these percentages refer only to the model used; owing to the effect of ambipolar electric fields, the equatorial concentration will be lower. It is evident that this technique has a sensitivity of a few percent to changes in the integrated light ion concentration.

The parameters of the light ion models calculated by using this technique are tabulated in the last three columns of Table 1 for each of the 14 groups of whistlers. Note the increase in scale height, owing to increase in temperature, with increasing radial distance. For groups with several whistlers, three concentrations, corresponding to $\bar{D} + \Delta D$, $\bar{D}$ and $\bar{D} - \Delta D$ are given.

To obtain an integrated measure of the ion concentration, we use the flux tube column density of ions, obtained by integrating the ion concentration over the volume of a flux tube and dividing by the equatorial flux tube area, to calculate the number of ions per unit L multiplied by L^2, a quantity of use in the study of radial diffusion. Using the definition of a flux tube, BA = constant, the column density N_c is calculated from

$$N_c = B_0 \int (n/B)\, ds \tag{4}$$

with the integral evaluated along the flux tube from one hemisphere to the other. Here, B_0 is the equatorial magnetic field strength at the flux tube, n is an ion model, and B is the magnetic field strength. In terms of N_c, the total number of ions per unit L multiplied by L^2, NL^2, is given by

$$NL^2 = (2\pi R_J^2)\, L^3 N_c \tag{5}$$

Figure 5 shows NL^2 for the two light ion models and for the heavy ion distribution. The values of NL^2 for the heavy ions are those given by *Bagenal and Sullivan* [1981]. Owing to the increased concentration in the equatorial region, the scale height model overestimates the value of NL^2. In contrast, the constant density model gives a lower limit on the value of NL^2.

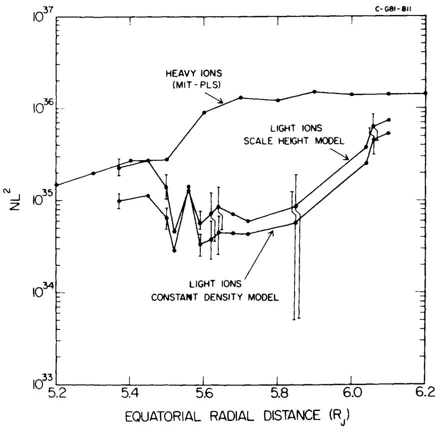

Fig. 5. The total number of ions per unit L multiplied by L^2, calculated by using equation (5), as a function of equatorial radial distance from Jupiter. This quantity is shown for both light ion models and the heavy ions. The bars define the range in NL^2 corresponding to the group dispersions $\bar{D} + \Delta D$, D, $\bar{D} - \Delta D$. The scale height model overestimates the value of NL^2 while the constant density model gives a lower limit on the value of NL^2.

Discussion

In this paper we have used whistler dispersion measurements and Io torus heavy ion concentrations to define two models for the light ion concentration over 14 L shells between $L = 5.2$ and 6.2. Because the heavy ion concentrations near the equator are typically an order of magnitude larger than the light ion concentration, the results obtained are mainly relevant to the light ion concentration outside of the torus. While the light ions are only known to have $A/Z < 8$, we have taken them to be protons in our calculation of the scale height. That the light ions are probably protons is supported by the fact that, since Io is only known to contribute heavy ions, they probably originate in Jupiter's primarily hydrogen atmosphere. The protons are probably injected into the magnetosphere due to the energetic particle impacts of atmospheric hydrogen and precipitating auroral ions. Models for this process have been worked out with results that depend on the concentration of light ions in the magnetosphere [*Thorne,* 1981]. The results reported in this paper may be of use in the further refinement of these theories.

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