

Anisotropy and proton density in the Io plasma torus derived from whistler wave dispersion

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Abstract. During the Voyager 1 encounter with Jupiter, a large number of whistler waves were observed. Previous studies have examined the dispersion of these waves and made estimates of the electron and light ion (i.e., proton) densities. The current paper reexamines this data, taking into account the revised temperatures of the torus species the additional data on ion composition from the Voyager UVS instrument and the role of thermal anisotropy on the plasma densities. These refinements in the density model drastically alter the implications of the whistler wave data. Both the thermal and the nonthermal species must be anisotropic to fit the whistler dispersions. The thermal component must have $T_{\perp}/T_{\parallel} > 1.75$ and the nonthermal component $3 < T_{\perp}/T_{\parallel} < 10$. The equatorial proton density is low, under 60 cm^{-3} in all cases. This results in a proton abundance (L shell proton content relative to the total ion content) of no more than 10%, approximately a factor of two lower than the conclusions of previous whistler analysis. At the high latitudes, the implied electron density results in a plasma frequency of under 20 kHz. Finally, it is evident from this analysis that not all of the whistler waves were propagating along the magnetic field lines, as was commonly assumed in previous work.

Introduction

Both abundance of protons and the thermal anisotropy in the Io plasma torus strongly affect the densities at high latitudes [Bagenal, 1994]. Protons might reasonably be expected in the plasma torus. Both the Jovian atmosphere and inward diffusion from the middle magnetosphere, where protons are known to be a significant constituent [McNutt *et al.*, 1981], are potential sources. Since protons would have such a large effect on the high-latitude densities, they are an important concern for plasma waves [Thorne *et al.*, 1995] and radio emissions [Lecacheux *et al.*, 1991; Goldstein and Goertz, 1983]. Thermal anisotropy is a critical factor in the spectral emissions of the torus [Brown, 1982] and studies of the source and chemistry of the plasma [Barbosa, 1994; She-mansky, 1988; Smith and Strobel, 1985], since the parallel temperature determines the scale height of the torus.

Some anisotropy is to be expected, since the ions are produced in a “pickup” distribution. The equilibrium distribution of torus ions is a balance between this anisotropic, non-thermal source and the various processes which thermal and isotropize the ions. The result would be something between a pickup and a Maxwellian distribution.

However, unlike other properties of the torus, these characteristics were not directly measured by the Voyager space-

craft. The plasma instrument onboard was only capable of measuring the perpendicular temperature [Bridge *et al.*, 1977]; no data on the parallel temperature or anisotropy were obtained. While protons are presumed to be a prominent species in the midlatitudes and high latitudes, they are only a minor constituent at lower latitudes and have a relatively low corotation energy. As a result, Voyager was unable to measure proton densities [Bagenal and Sullivan, 1981] in the plasma torus, although protons were observed elsewhere in Jupiter’s magnetosphere. These values are the primary free parameters in the existing density models [Bagenal, 1994].

The observation of whistlers by the Voyager plasma wave instrument offer a means for estimating these parameters. During the Voyager 1 encounter with Jupiter, a large number of whistlers were observed. In addition to indicating the existence of lightning in Jupiter’s atmosphere, these whistlers also provide information about the midlatitude and high latitude regions of the planet’s magnetosphere. Figure 1 shows two examples of whistlers observed near Jupiter. The signals are dispersive, with lower frequencies propagating more slowly than higher ones. The degree of dispersion is a measure of the path-integrated electron density.

Traditionally, whistlers are studied in the limit, $ff_g \ll f_p^2$ (where f is the frequency of the wave, f_p and f_g are the electron plasma and gyrofrequencies.) In that case, the arrival time of the wave is described by Eckersley’s law.

$$\begin{aligned} t &= t_0 + \frac{1}{c} \int n \, ds \\ &= t_0 + \frac{D}{\sqrt{f}} \end{aligned} \quad (1)$$

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Paper number 95JA02212.
0148-0227/96/95JA-02212\$05.00

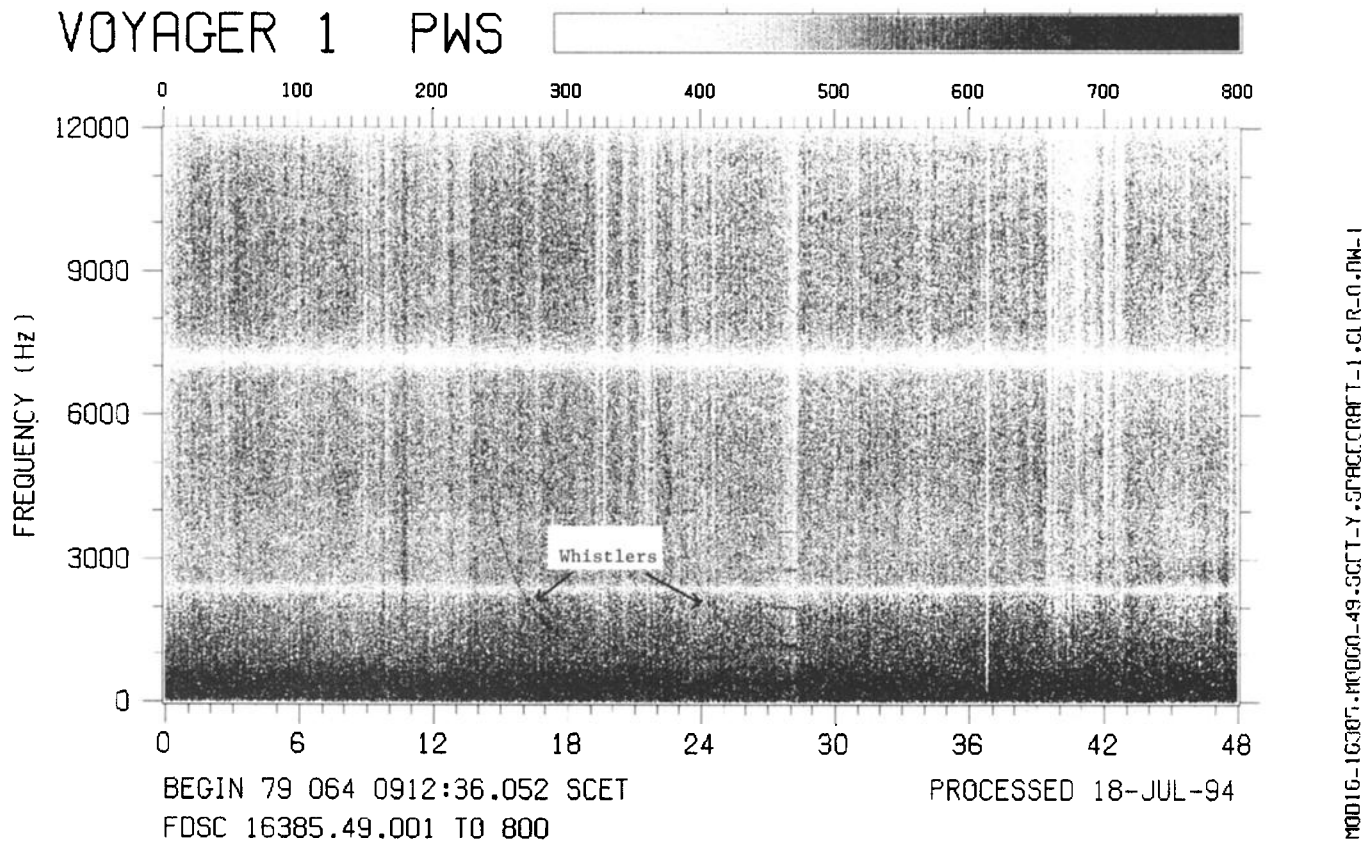


Figure 1. Two examples of whistler waves observed by Voyager 1, Day 64, 1979, as displayed by the newer analysis software used in the present work.

Where D , the dispersion of the wave, is defined as

$$D \equiv \frac{1}{2c} \int \frac{f_p}{\sqrt{f_g}} ds \propto \int \sqrt{\frac{n}{B}} ds \quad (2)$$

n is the electron density, and B the background magnetic field.

Given a model of density and magnetic fields, the expected dispersion can be calculated. This result can then be compared to observations and used to select the free parameters of the model to so as to match the observations. The Voyager measurements have previously been analyzed in this way [Gurnett *et al.*, 1979; Menietti and Gurnett, 1980; Gurnett *et al.*, 1981; Tokar, 1982; Kurth *et al.*, 1985], finding that a proton abundance of approximately 15% was consistent with the observed whistler dispersions. However, more recent work makes a reexamination of this data useful.

The previous studies used a ion temperatures based on the original results of the Voyager plasma instrument [Bagenal and Sullivan, 1981]. Since then, these estimates have been revised [Bagenal *et al.*, 1985] to correct a systematic error, a factor of two in perpendicular temperature, in the initial analysis. The current work uses the revised temperatures. As a result, the plasma torus modeled here is less closely confined to low latitudes. Since a larger, high density region would produce more dispersion in the whistlers, this change dramatically reduces the amount of protons necessary to match the observed waves. The ion composition of the torus has

also been refined by the Voyager ultraviolet spectrometer data [Bagenal *et al.*, 1992].

Nor were the effects of thermal anisotropy included in the earlier work. Only in recent years has this topic become a part of published density models [Huang and Birmingham, 1992; Bagenal, 1994]. Anisotropy tends to concentrate ions in the low latitudes by altering the parallel temperature, and therefore the scale height and by adding a magnetic mirror force.

Finally, increased computer capability now allows for a much more exact, numerical integration of the predicted dispersion. The work of a decade ago typically relied on reasonable but inexact approximations. These approximations, regarding the wave dispersion and density model, will be discussed in more detail in a later section.

Observations

During the Voyager 1 encounter with Jupiter, 167 whistlers were observed. Of these, 90 were sufficiently well resolved to be analyzed in detail. They were observed during three regions of the spacecraft's orbit, as illustrated in figure 2.

The whistlers from regions 1 and 3 have high dispersions, 260 ± 35 and 475 ± 50 s Hz^{0.5} respectively. In contrast, those from region 2 have dispersions of 65 ± 20 s Hz^{0.5}. For this reason, the regions 1 and 3 whistlers are believed to have passed through the equatorial plane and the high-density regions of the plasma torus, while the region 2 whistlers did

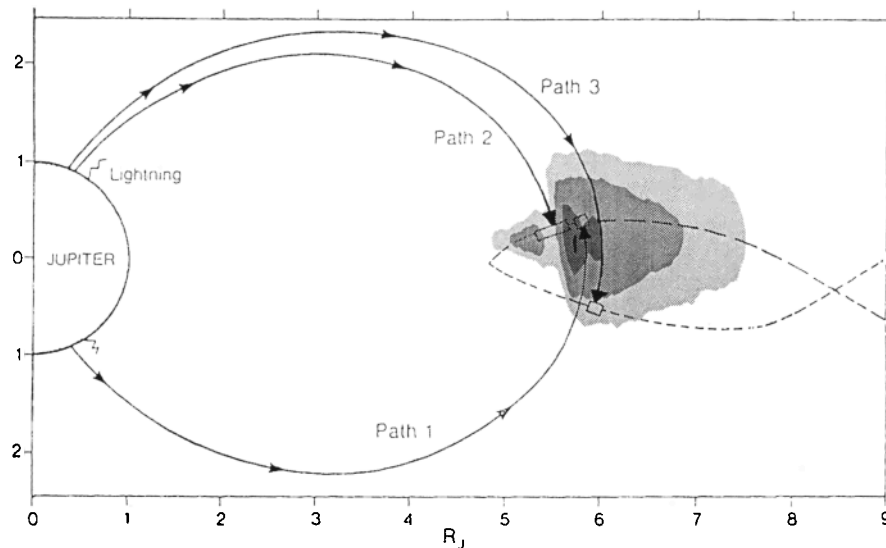


Figure 2. The Voyager trajectory, in the radius-latitude plane, with the three periods of whistler waves observations marked [from Gurnett, 1981]. Superimposed are contours of electron density based on Bagenal [1994]. Arrows indicate presumed whistler ray paths.

not, instead traveling the more direct, lower-dispersion route from the Jovian ionosphere [Menietti and Gurnett, 1980], as shown in figure 2.

The whistlers may be divided into several groups, each of representing a 40-s period of observations [Tokar, 1982; Kurth et al., 1985]. (Note that Tokar used only 14 of these groups in his analysis.) Table 1 shows the time, spacecraft position, magnetic *L* shell and maximum frequency of these groups as well as the dispersion of one or two members.

In most cases, the dispersion of these waves has been recalculated. The frequency of peak intensity was determined for each 60-ms sweep of the plasma wave instrument. This technique is accurate to ±3% and discussed in more detail by Ansher [1992]. The resulting time-frequency data were fit to

Eckersley's law using a numerical χ^2 minimization. These results were supplemented with other, previously published reductions of the whistler data, as indicated in table 1.

Within each group, there is substantial variation in the measured dispersion, of order ±5%. This suggests that these waves, despite having been observed at almost the same time and place, did not all propagate along exactly the same path. With the improved analysis of dispersions, this variation is the primary source of uncertainty in the data.

The maximum frequency of each wave is also of interest. Since whistler waves can only propagate below the plasma frequency, the maximum, observed frequency sets an absolute lower limit on the electron density [Gurnett et al., 1981]. However, this is not the only effect that may limit the fre-

Table 1. Whistler Dispersions and Maximum Frequencies, Day 64, 1979

Time, SCET	Spacecraft Position			<i>L</i> Shell, <i>R_J</i>	Dispersion <i>sH z</i> ^{0.5}	Maximum Frequency kHz
	Radius, <i>R_J</i>	Latitude, deg	Longitude, deg			
0913	5.799	-5.139	201.5	5.838	259 247	4.38 6.18
0926	5.670	-5.265	206.7	5.702	255 [†]	6.9 [‡]
0931*	5.630	-5.318	208.8	5.659	72 [†]	4.2 [‡]
0935*	5.589	-5.362	210.6	5.616	69 [†]	3.6 [‡]
0937*	5.579	-5.318	211.4	5.607	57.3	4.08
0941*	5.540	-5.141	212.8	5.568	48.3 52.9	3.63 3.84
0944	5.516	-5.441	213.9	5.539	72 [†]	3.0 [‡]
0947	5.492	-5.467	215.0	5.513	62.9	3.66
0948*	5.484	-5.476	215.4	5.505	40.1	4.80
0950	5.468	-5.489	216.1	5.488	64 [†]	5.1 [‡]
0957	5.418	-5.542	218.5	5.435	83 [†]	5.1 [‡]
1006*	5.345	-5.615	222.0	5.358	71 [†]	5.4 [‡]
1016	5.277	-5.681	225.5	5.286	42.0	5.58
1022	5.235	-5.721	227.7	5.242	64.3	2.93
1505	5.892	-2.916	325.4	6.003	390 [†]	4.0 [‡]
1508	5.908	-2.888	326.0	6.021	410	6.48
1511	5.948	-2.868	327.5	6.066	428	5.70

*Whistlers excluded from final analysis.

[†]Average group values from Tokar et al. [1982].

[‡]Average group values from Kurth et al. [1985].

quency range of whistlers [Helliwell, 1965]. The details of these various mechanisms are beyond the scope of the present paper. However, it is important to note that different high-frequency cutoffs may imply differences in the propagation or ray path of the whistlers.

Whistler Waves

The analysis of Jovian whistlers is slightly more complex than the terrestrial case. The traditional approximation, $ff_g \ll f_p^2$ does not hold in the midlatitudes and high latitudes. Therefore a more general form of the dispersion is required.

From Eckersley's law, the dispersion may also be expressed as

$$D = -\frac{1}{2} f^{3/2} \frac{df}{df} \quad (3)$$

The exact index of refraction for whistler waves [Helliwell, 1965] is

$$n = \frac{1 + \frac{1}{2} \frac{f_p^2 f_g}{f(f_g - f)^2}}{\sqrt{1 + \frac{f_p^2}{f(f_g - f)}}} \quad (4)$$

Over the region and frequency range of interest, $f \ll f_g$. In this limit, the dispersion can be expressed as

$$D = \frac{1}{2c} \int \frac{f_p}{\sqrt{f_g}} \left(1 + \frac{ff_g}{f_p^2} \right)^{-3/2} ds \quad (5)$$

This definition goes to the traditional form in the appropriate limit but is also applicable even when $f_p < f_g$.

To compute the dispersion, some description of the ray path is required. Previous studies of jovian whistlers have assumed that the wave propagate along the magnetic field lines. Ray tracing models suggest that this will generally be correct [Menietti and Gurnett, 1980] and local density variations may act as a "duct," confining along a given field line [Helliwell, 1965]. However, other analysis [Thorne et al., 1995] implies that significant deviations from parallel propagation are also possible. In addition, a ducted whistler may not give an accurate measure of the electron density. By nature, it would have been confined to region with a higher or lower density than the background. As a result, its dispersion would be a measure of the density in the duct, rather than the average density. These possible differences in wave propagation may account for the $\pm 5\%$ variation in observed dispersions mentioned above.

The current model will assume parallel propagation, for lack of a better description of the ray path. However, any dispersion that can not be accounted for will be attributed to these limitations of the model; nonparallel propagation, density variations within a duct, etc., and these data will not be used in the estimates of proton density and thermal anisotropy.

Density Model

The dispersion is an integral over the entire path of the whistler and is not a direct measure of local density. As a result, some model of the density must be adopted.

Previous studies of Jovian whistler waves have made various assumptions: A step function, with one, constant value within the torus and another, constant value at higher latitudes [Gurnett et al., 1979]; an exponential scale height [Gurnett et al., 1981]; an exponential distribution of light ions plus a fixed background of heavy ions [Tokar, 1982]; etc.

However, even an exponential scale height model is only exact for a single-species plasma. When there are multiple species present, an ambipolar electric field is generated and produces a different density structure. The Voyager PLS instrument observed seven species. In addition, several of the species show signs of a nonthermal distribution [Bagenal and Sullivan, 1981; Brown, 1982] and such distributions are also suggested by theoretical models [Smith and Strobel, 1985]. In the present work, as in previous models of density structure [Bagenal, 1994], these species are modeled as a sum of two Maxwellians: A cold, high-density Maxwellian, representing the nearly Maxwellian "core" population and a hot, low-density Maxwellian to approximate a high-energy tail. These are referred to as the "thermal" and "nonthermal" components in this paper.

The present work uses the diffusive equilibrium model to make more accurate calculations of the density. This model assumes that, along magnetic field lines, the electric, centrifugal and pressure forces balance

$$0 = \left(n_{\alpha} q_{\alpha} \vec{E} + n_{\alpha} m_{\alpha} \vec{f}_{cent} - \vec{\nabla} \cdot P \right) \cdot \frac{\vec{B}}{|B|} \quad (6)$$

By manipulating this expression and given a magnetic field geometry, an equation for density can be found. This relation holds for both Maxwellian and anisotropic, bi-Maxwellian plasmas, so long as the anisotropy does not vary.

In fact, temperature and anisotropy are not constant along a field line but may be described analytically. It can be shown [Huang and Birmingham, 1992] that, in a bi-Maxwellian plasma where the adiabatic invariants are preserved, the parallel temperature will remain constant and the perpendicular temperature varies as

$$T_{\perp} = T_{\perp 0} \left[A + (1 - A) \frac{B_0}{B} \right]^{-1} \quad (7)$$

Where A is the the anisotropy, T_{\perp}/T_{\parallel} , and the subscript, 0, denotes values at some reference position.

This has a significant effect on the distribution of an anisotropic plasma. Since A decreases toward the higher latitudes, the magnetic mirror force similarly decreases. Thus the anisotropic, nonthermal (~ 150 eV) component of the plasma torus may have a much greater vertical extent and contribution to whistler dispersion than might otherwise be expected. This effect may also apply to the "thermal" (~ 50 eV) component, typically assumed to be in an isotropic distribution. Recent studies [Herbert and Sandel, 1995; Taylor et al., 1994; Thomas, 1995] suggest that these species may also be anisotropic.

Combining this form for the thermal structure with the diffusive equilibrium model for density gives

$$n_{\alpha}(s) = n_{0\alpha} \left[A + (1 - A) \frac{B_0}{B} \right]^{-1} \quad (8)$$

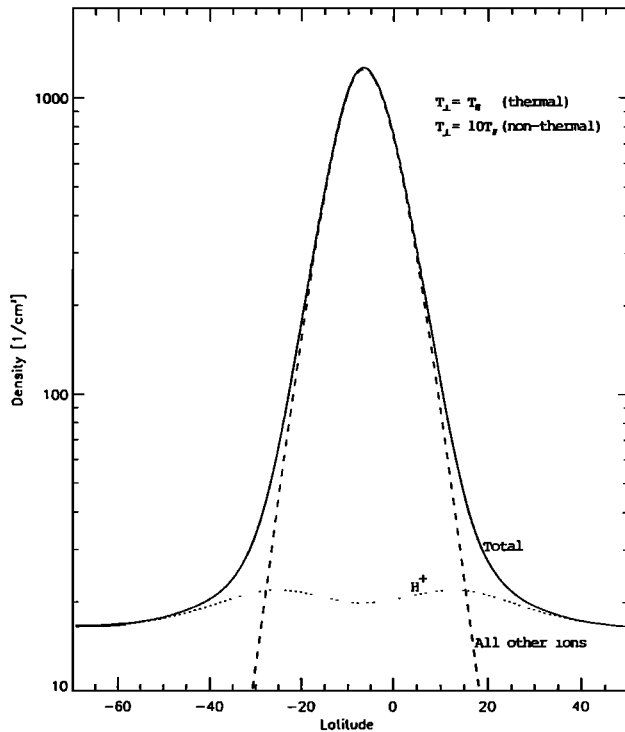


Figure 3. A typical density profile based on the diffusive equilibrium model, for $L = 6.58R_J$. The solid line shows the electron density; dotted the proton density and dashed the sum of the other, heavier ions.

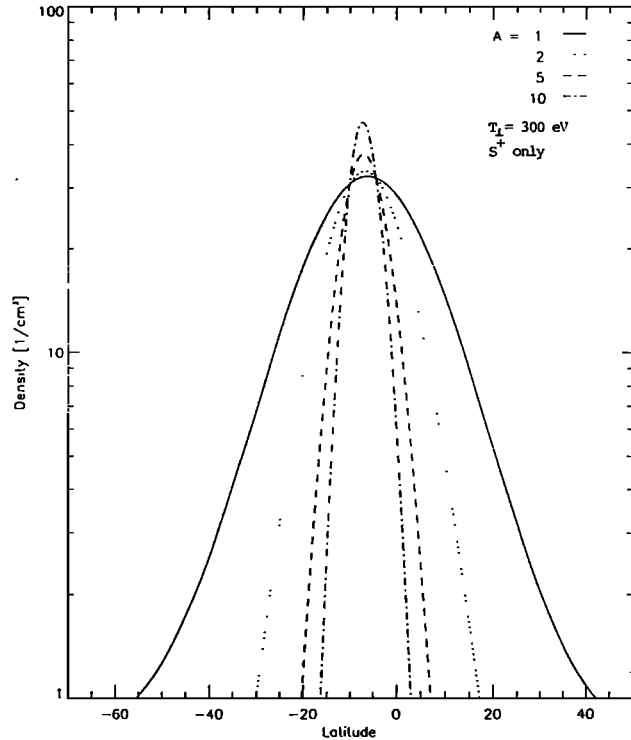


Figure 4. Density profiles for the nonthermal S^+ ion at $L = 6.58R_J$, for several values of A .

$$\exp \left[\frac{1}{2} \frac{m_\alpha}{T_{\alpha||}} \Omega_J^2 (r^2 \cos^2 \Theta - r_0^2 \cos^2 \Theta_0) - \frac{q_\alpha}{T_{\alpha||}} \Phi \right]$$

where the reference point must be along the same field line as s . While Φ , the ambipolar electric potential, can not be solved for analytically, it can be calculated numerically under the constraint of local charge neutrality.

Figure 3 shows an example of a density profile computed in this way. Note the reduced proton density near the equator and that the heavy ion density drops off more rapidly than would a Gaussian distribution. These are the result of the ambipolar electric field. Figure 4 shows a distribution of an anisotropic species, in this case, 300 eV S^+ , for various values of A .

A model of the magnetic field is required, in addition to one of density. This analysis used the Goddard Space Flight Center "O4" model [Acuña *et al.*, 1983]. The Connerney, Acuña and Ness model of the current sheet was not used, since its assumptions are least accurate in the region of interest [Connerney *et al.*, 1981]. In any case, the contribution of the current sheet in this region is small.

Method and Results

This model of whistler wave dispersion is, unfortunately, poorly constrained. At each position, there are three free parameters in the model: Proton density and the anisotropies of the nonthermal and thermal components. Even this assumes that all species of the thermal component have the same anisotropy and all non-thermal species also have some other, common value. While this number of free parameters

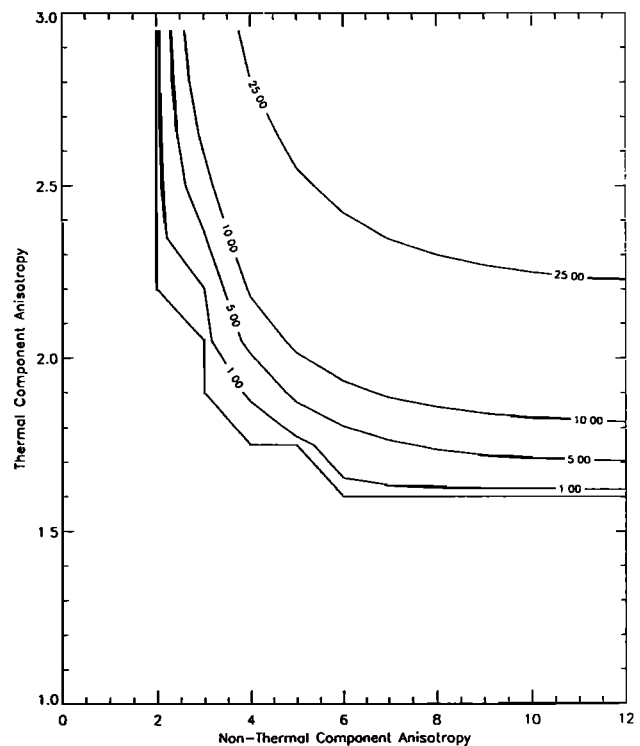


Figure 5. An example of the proton density implied by whistler dispersions, here the 0926 whistler, as a function of A_t and A_{nt} . Contours show the density at the spacecraft in units of $1/cm^3$. The outer, unlabeled contour marks the division between allowed and forbidden values of A_t and A_{nt} .

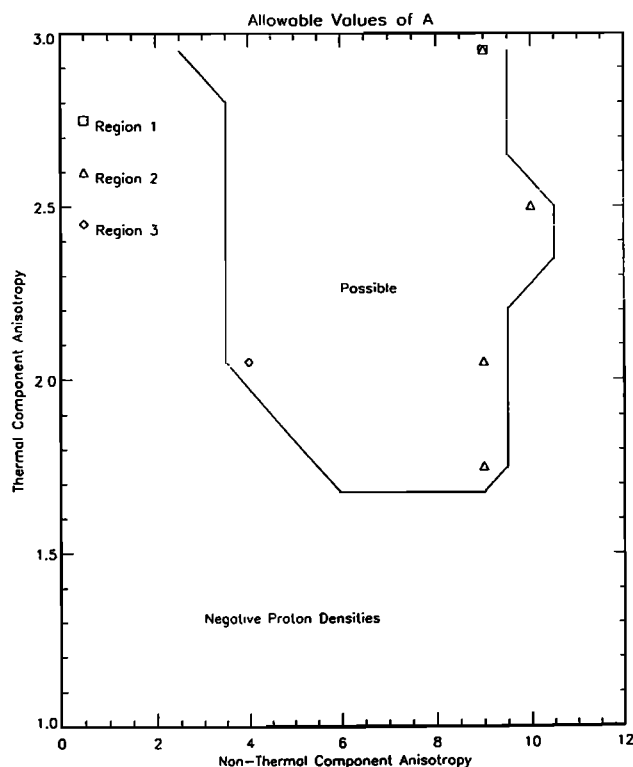


Figure 6. The range of anisotropies which can and cannot potentially reproduce the observed whistler dispersions.

makes it impossible to calculate exact values for all three parameters, the whistler dispersions are sufficient to place limits on them.

For each of the whistlers examined, (5) was integrated numerically at a frequency of 3.5 kHz for all combinations of the thermal and nonthermal anisotropies,

$$A_t \in \{1.0, 1.15, 1.3, \dots, 2.8, 2.95\} \quad (9)$$

$$A_{nt} \in \{1, 2, 3, \dots, 11, 12\}$$

The proton density was then adjusted to fit the modeled dispersion to the observed value, giving proton density as a function of A_t and A_{nt} . In many cases, no physically meaningful (i.e., positive) value of n_p could reproduce the observed dispersion; even assuming no protons were present, the modeled dispersion was too great. Therefore these combinations of A_t and A_{nt} may be ruled out as inconsistent with whistler observations. Figure 5 shows one example of these results. These limits are of particular interest for the thermal component. In almost no cases could an isotropic, thermal component match the observed dispersions.

For seven of the nineteen whistlers examined, there was no combination of $A_t \leq 2.95$ and $A_{nt} \leq 12$ that could reproduce the the observed dispersions. Specifically, the whistlers observed between 0931 and 0941, at 0948 and at 1006. These whistlers, however, have many common properties that set them apart from the others: They were all observed in region 2; they typically have lower maximum frequencies than the other whistlers; and were generally observed just inward of $L = 5.6$. These features suggest that these anomalous whistlers may not have propagated in the assumed manner. Since they were region 2 observations, the bulk of their ray

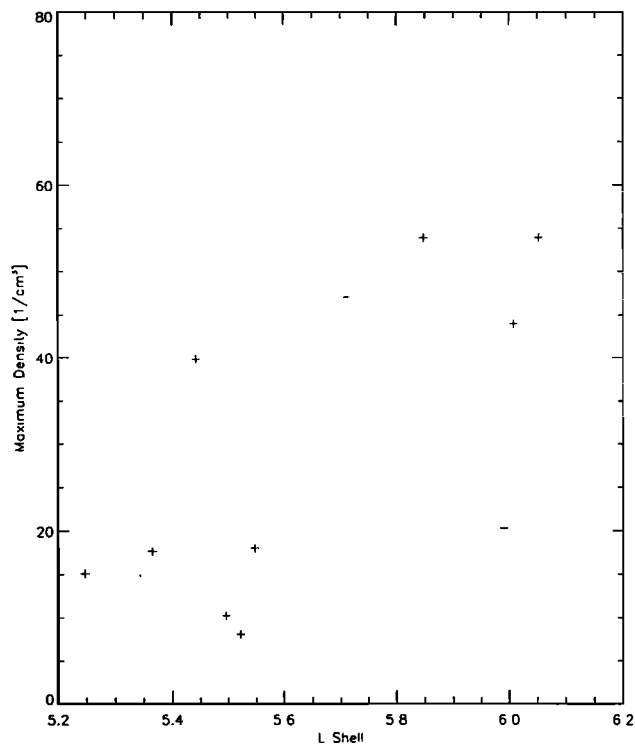


Figure 7. The maximum proton densities consistent with the observed whistler dispersions. Values are those predicted at the centrifugal equator.

path was in the midlatitudes and high latitudes. At those latitudes, $f_g > f_p$, which would alter the restrictions on group velocity and the conditions for ducting. The systematically lower maximum frequencies also suggest that, in some manner, these seven whistlers were different from the others. Finally, the location in which they were observed, immediately inward of the "ribbon" feature in the plasma torus, is known to be one of sharp density gradients. These gradients could potentially affect whistler propagation and dispersion. The inner edge of the "ribbon" feature has previously been studied as a region of nonlinear processes producing a whistler mode "auroral hiss" [Morgan *et al.*, 1994; Das and Ip, 1992]. Because these issues cast doubts on the applicability of the present model to these seven whistlers, they will not be used in the following analysis.

To place further limits on anisotropy, it was assumed that the thermal and nonthermal anisotropies are constant throughout the plasma torus. Under this constraint, there are only a small range of anisotropies that consistently reproduce the observed dispersions. Figure 6 shows the possible values of A_t and A_{nt} . In general, the thermal component must have an anisotropy of 1.75 or greater; the nonthermal component is limited to $3 < A_{nt} < 10$.

While this does not restrict the solutions enough to specify proton densities, it does significantly limit the possible range. Figure 7 shows the maximum proton densities predicted by the model. These upper limits are a factor of 2 or 3 lower than the proton densities found by previous whistler research. This is largely due to the revised, higher temperatures of the current density model. Since the higher temperatures result in a larger vertical extent to the torus and therefore greater

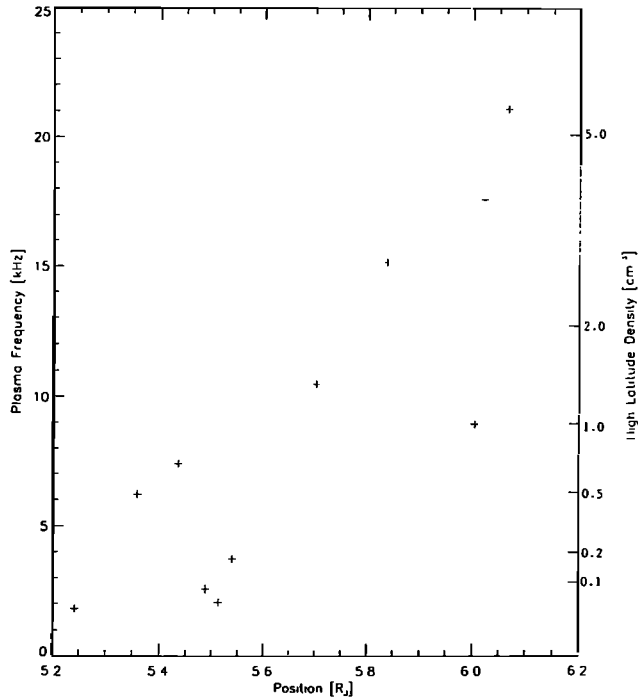


Figure 8. The upper limit on high-latitude plasma frequencies consistent with the observed whistler dispersions. Note that the high-frequency cut-off of the whistlers also sets a lower limit of 3 – 7 kHz

dispersion, there is less need for protons producing dispersion at mid- and high latitudes.

As well as setting an upper limit on the equatorial proton density, these results also imply an upper limit on the electron density and plasma frequency at the high latitudes. Here the densities are more constant than in the plasma torus; the limit is applicable to the entire region above, roughly, 50° latitude. Figure 8 shows this implied upper limit. These numbers are, in addition, consistent with analysis of the decametric radio emissions which suggest a high-latitude plasma frequencies of under 20 kHz [Lecacheux et al., 1991].

A final parameter of interest is the total content of the *L* shell. This value, and especially its radial dependence, is an indicator of the radial transport processes at work [Siscoe, 1978]. Typically expressed as *L*² times the total number of particles, it is equal to

$$NL^2 = 2\pi R_J^2 L^3 \int n \frac{B_0}{B} ds \quad (10)$$

Figure 9 shows the maximum *L* shell content of protons based on the above densities, numerically integrated up along the field lines. This upper limit is a factor of one and a half to two lower than the proton content estimated by Tokar [1982], and represents a proton abundance of under 10%. Although no other qualitative conclusions can be drawn from such a limit, several qualitative features are apparent. The hydrogen content decreases with decreasing radius, suggesting that the source of protons (unlike the other torus species) is located farther out than *L* = 6.2 *R_J* and diffuses inward. There may be a drop in proton content near the orbit of Io, which would be consistent with previous suggestions of “sweeping” or absorption of ions by Io. Although Io is more often thought

of as a source of plasma, this would not be the case for protons. However, this drop (presuming it is not an artifact of the maximum rather than actual proton content) may also be a local effect. At the time this observation was made, Voyager was nearing its flyby of Io; the reduction may be limited to Io’s vicinity rather than a general, longitudinally invariant, property.

Conclusions

The analysis of whistler wave dispersion can constrain the free parameter of a density model. The current analysis has set limits on the anisotropy of the nonthermal population, of between 3 and 10, and limited the proton abundance to less than 10%. The radial variation of this abundance is consistent with a source of protons outside of 6 *R_J*. More importantly, the current examination of whistlers argues that the cooler, thermal population must be anisotropic as well. The free parameters in the density model could not be set to fixed, empirically determined values. At the same time, the whistlers observed by Voyager are only one of several sources of information on anisotropies and proton densities.

First, spectral observations may be able to estimate the relative fraction of thermal and nonthermal ions. Some work along these lines has already been done [Brown, 1982], and additional efforts are in progress. Second, the scale height of the torus is a measure of parallel temperatures and therefore provides information on the anisotropy. This can be observed by Earth-based telescopes, by reexamination of the Voyager UV spectrometer data [Herbert and Sandel, 1995] and by the Galileo spacecraft’s extreme ultraviolet instrument [Hord et al., 1992]. Nor is the EUVS the only instrument on Galileo which may address these questions. The plasma instrument, a differential, hemispheric plate detector, is able to measure

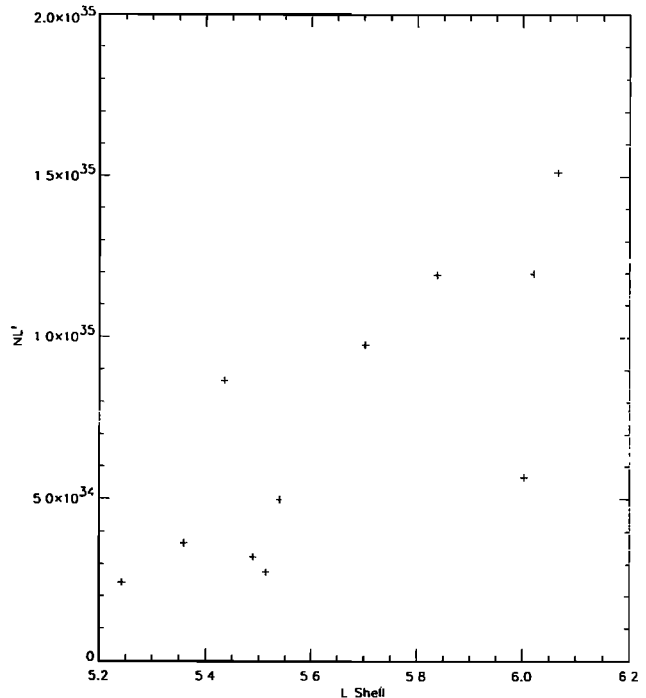


Figure 9. The maximum *L* shell content consistent with the observed whistler dispersions.

small regions of phase space [Frank *et al.*, 1992] and thereby observe fluxes of protons in isolation from heavy ions (due to the differing thermal velocities and the much broader region of phase space occupied by protons) and make measurements of both parallel and perpendicular temperatures. Finally, the Galileo plasma wave instrument could also make additional observations of whistlers. The sensitivity and requirements for observing whistlers are certainly within the instrument's capability [Kurth *et al.*, 1985; Gurnett *et al.*, 1992]. However, as a result of the necessities of the "low data rate" mission, the instrument will only be operating in the appropriate mode for a small fraction of the spacecraft's pass through the torus. While theoretically within the instrument's capabilities, there may be no whistler to observe during these limited periods. Such observations would be very fortunate but are also unlikely.

Perhaps the more effective means to exactly specify anisotropies and proton densities would be a combination of all these sources of data. While no single source, perhaps, can uniquely determine these quantities, together they might allow a specific answer.

Acknowledgments. The Editor thanks D.E. Shemansky for his assistance in evaluating this paper.

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(Received March 1, 1995; revised July 6, 1995; accepted July 18, 1995.)