JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 90, NO. A2, PAGES 1755–1757, FEBRUARY 1, 1985

Revised Ion Temperatures for Voyager Plasma Measurements in the Io Plasma Torus

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We have discovered that an error was made in computing ion temperatures for some of the results derived from the positive ion data from the plasma science (PLS) experiment on the Voyager spacecraft. The reported results directly affected by this error are the ion temperatures in the inner magnetosphere of Jupiter given by Bagenal et al. (1980) and Bagenal and Sullivan (1981) plus a single ion temperature calculated from Voyager 1 data obtained in Saturn's magnetosphere and quoted by Bridge et al. (1981). The ion temperatures quoted for the torus region in the original Jupiter *Science* article (Bridge et al., 1979) and all of the ion temperatures in the middle magnetosphere of Jupiter (McNutt et al., 1981) were derived independently and are unaffected by the error.

DISCUSSION OF ION TEMPERATURE MEASUREMENTS

We are currently reanalyzing much of the positive ion data obtained by the Voyager plasma science (PLS) experiment during the Jupiter encounters. In the course of that analysis it became apparent that some ion temperatures obtained in previous work were a factor of 2 lower than those derived from the current analysis program. This discrepancy was traced to an error which affected some but not all of the earlier results.

The error, which caused the ion temperature to be quoted at half of the correct value, was introduced because the "ion thermal speed" was defined inconsistently in separate parts of the analysis of the torus data. The energy-per-charge spectra obtained by one of the PLS detectors during the inbound traversal of the Io torus are shown in Figure 5 of *Bagenal and Sullivan* [1981]. In the initial analysis of these spectra, each ionic species was assumed to have an isotropic reduced distribution function in velocity space which could be described for a specified direction (such as along the detector normal) by a Maxwellian function

$$f(v) = nw^{-1}(2\pi)^{-1/2} \exp\{-(v - V)^2/(2w^2)\} \tag{1}$$

involving three independent parameters: the bulk speed of the ions in the specified direction V, the total number density n, and the thermal speed w. For the above form of $f(v)$, w is related to the ion temperature by $w = (kT/m)^{1/2}$, where m is the mass of ion. The error occurred when the values of the ion thermal speed derived from the data in this way were later converted to ion temperatures using the more common definition of $(2kT/m)^{1/2}$ for the thermal speed. Thus the ion temperatures that emerged from the analysis were a factor of 2 lower than they should have been. Although the values derived for local density and bulk speed are obviously not affected by this error, the underestimate of the ion temperatures has two major effects. First, the incorrect ion temperatures were used to calculate scale heights for different ionic species. Since these scale heights form the basis for the two-dimensional plots of plasma density in the torus (as a function of cylindrical radial distance and distance from the centrifugal equator, z), the contour plots given by *Bagenal et al.* [1980] and *Bagenal and Sullivan* [1981] are incorrect. In addition, values of the flux tube content per unit L times the L shell parameter squared (NL^2), derived using these temperatures, are underestimates by about a factor of $(2)^{1/2}$. The following section contains a summary of published results affected by this error in calculating the ion temperatures.

SUMMARY OF THE EFFECTS ON PUBLISHED RESULTS

The ion temperatures derived for the Io torus region by *Bridge et al.* [1979] and for the middle magnetosphere of Jupiter outside of 10 R_J by *McNutt et al.* [1981] are correct as given. The ion temperatures derived by *Bagenal and Sullivan* [1981] and shown in Figure 7 of that paper should be increased by a factor of 2, as should the ion temperatures in Figure 1 of *Bagenal et al.* [1980] (however, see the following section for a discussion of the inherent uncertainties in the ion temperature determination). The temperatures inside of 10 R_J only, shown in Figure 11 of *McNutt et al.* [1981], should also be increased by a factor of 2. With regard to the single incorrect estimate in Saturn's magnetosphere, the thermal speeds quoted in Figure 5 of *Bridge et al.* [1981] for ions with mass-to-charge ratios of 1 and 16 should be 38 and 28 km s^{-1}, respectively, where thermal speed is defined as $(2kT/m)^{1/2}$.

The ion temperatures in the inner magnetosphere of Jupiter were used to extrapolate the local measurements of ion density away from the spacecraft location along magnetic field lines; these extrapolated values of ion density describe the spatial distribution of plasma in the Io torus and were given in the form of density contour plots by *Bagenal et al.* [1980] and by *Bagenal and Sullivan* [1981].

Correction of the ion temperatures results in a torus which is more extended in latitude than that shown in these papers. If we approximate the density distribution along a field line as a Gaussian function,

$$n(z) = n(z = 0) \exp\{-(z/H)^2\} \tag{2}$$

where the scale height $H \propto (T)^{1/2}$, it is evident that the twofold increase in temperature means that the torus should be ~40% more extended in the z direction. The spatial distribution of torus plasma has been recalculated in the same manner as that of *Bagenal and Sullivan* [1981] using temperatures corrected by a factor of 2. The resulting map of positive ion charge density (in elementary charges per cubic centimeter) is shown in Figure 1.

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Paper number 4A8310.
0148-0227/85/004A-8310$02.00

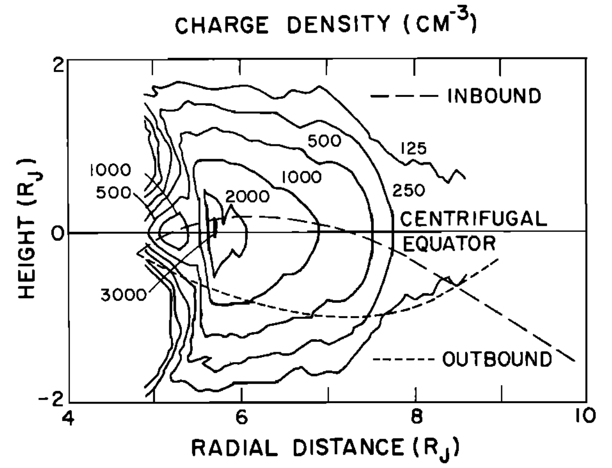

Fig. 1. Revised isodensity contour map of positive charge density (in elementary charges per cubic centimeter) as a function of centrifugal distance and height above the centrifugal equator.

If we take the boundary of the plasma torus to be defined as the 250 cm^{-3} contour of the electron density map, the total volume was estimated to be 7.7×10^{31} cm^3 (212 $R_J{}^3$) before correcting the temperature. Using the corrected contour map in Figure 1, the volume is increased by 30% to 1.0×10^{32} cm^3 (287 $R_J{}^3$) and is equivalent to a uniform torus with major and minor radii of 6.0 and 1.56 R_J, respectively. Only 3.0% (27%) of this volume is occupied by charge densities of over 2000 (1000) cm^{-3}, while these regions of high density contribute 9% (48%) of the total of 9.1×10^{34} elementary charges. As an aside, we note that the average density is only 875 cm^{-3}; this is considerably less than values generally used in the literature for the Voyager 1 epoch in studies of the torus.

Values of the quantity NL^2 have been derived using the scale height approximation for the density distribution given in (2) and integrating over z to obtain

$$NL^2 = \sum_i 2\pi^{3/2} R_J{}^2 L^3 n_i(z = 0) H_i \qquad (3)$$

Thus the erroneous ion temperatures caused the value of NL^2 to be underestimated by a factor of $\sim(2)^{1/2}$.

Values of NL^2 derived from the Voyager data have been used by various authors to calculate rates of plasma diffusion in the torus region [*Richardson et al.*, 1980; *Richardson and Siscoe*, 1981; *Siscoe et al.*, 1981; *Richardson and Siscoe*, 1983*a*; *Cheng et al.*, 1983]. *Tokar et al.* [1982*a*] used the plasma distribution derived by *Bagenal and Sullivan* [1981] to calculate the dispersion that would be expected if the whistlers observed by the Voyager plasma wave experiment had traveled from the ionosphere of Jupiter to the spacecraft. The electrons accompanying the torus ions were insufficient to produce the observed dispersion, and *Tokar et al.* [1982*b*] inferred that light ions, such as protons, had escaped from Jupiter's ionosphere and populated the mid-latitudes between the torus and the ionosphere, contributing a further 10–20% to the total electron content of these L shells. Correcting the ion temperatures by a factor of 2 in the warm torus would increase the total plasma content by ~40% which may produce far greater frequency dispersion of the whistlers than observed (however, see the discussion concerning temperature below). Without repeating the work of *Tokar et al.* [1982*a*, *b*] it is not possible to accurately determine the constraint placed by the observed whistler dispersions on the total flux tube content.

Finally, another important quantity that was derived from the PLS ion measurements was the Alfvén speed in the torus. Since the Alfvén speed is inversely proportional to only the square root of the local mass density, the corrected ion temperatures produce little change in the contour map of Alfvén speed shown in Figure 15 of *Bagenal and Sullivan* [1981]. The average time taken by an Alfvén wave to travel along field lines between Io and the ionosphere of Jupiter [*Bagenal*, 1983] should be increased by ~20% to 400 s owing to the extension of the torus. The range in travel times due to the variation in Io's position in the torus becomes about 200 to 800 s.

UNCERTAINTIES IN THE MEASUREMENTS OF ION TEMPERATURES

The ion data obtained inside ~5.7 R_J allowed accurate determination of the temperatures of the major ionic species [*Bagenal and Sullivan*, 1981; *Bagenal*, 1985]. In this cold inner torus, then, the factor of 2 correction to temperatures discussed above reflects the physical conditions in that region. However, outside of ~5.7 R_J, in the warm torus, there are inherent difficulties in the determination of ion temperatures. We currently feel that an increase of a factor of 2 in published ion temperatures in that region, although mathematically correct, probably is not physically realistic; on physical grounds an increase in published values of a factor around 1.5 is probably more appropriate in the warm torus for the following reasons. First, the broad velocity distributions of the warm plasma produce a very flat energy-per-charge spectrum in which the individual peaks of the ionic species cannot be resolved. Thus the parameters V, n, and w for each species are not well constrained by the data. Imposing the condition that all the ions should have the same temperature would reduce the number of free parameters and improve the fit.

However, for the isothermal approximation to be valid the time scale for thermal equilibrium between the different heavy ion species must be appreciably less than the characteristic time for diffusive loss. For the thermal (~60 eV) multispecies torus plasma ions the time for equilibration via ion-ion Coulomb collisions is about 5 days, and the diffusion time scale is 10 to 100 days. Thus the isothermal assumption is probably reasonable for the bulk of the ions. However, new ions are continuously created at pickup energies of 300 to 600 eV, and these ions maintain a high-energy tail in the ion distribution at energies well above the peak of the thermal distribution. This hot component will broaden the energy-per-charge spectra and increase the ion temperatures derived under the assumption of thermal equilibrium. A preliminary inspection of the high-energy tail of the spectrum suggests 10–20% of the ions are hotter than the thermal population. These numbers are consistent with both theoretical studies [*Barbosa et al.*, 1983; *Richardson and Siscoe*, 1983*b*] and spectral observations of optical emissions from S^+ ions reported by *Brown* [1982].

A study of the ionic composition of the warm torus using data from both the PLS detector and the Voyager ultraviolet spectrometer is in progress and it is hoped that, as a result of reducing the number of free parameters, the ion temperature can be better constrained. Meanwhile, the original analysis of *Bagenal and Sullivan* [1981] probably overestimated the width of the velocity distributions because of the presence of nonthermal tails, and hence we believe the temperature of the thermal ion population outside 5.7 R_J to be only a factor ~1.5 greater than their results and not the full factor of 2. We must be cautious in comparing local measurements made by Voyager 1 in 1979 with remote observations made using ground-based telescopes over a period of several years. Nevertheless, we suggest that the ion temperatures reported here are consistent with the temperatures of S^+ and S^{2+} ions obtained from spectral measurements of line emissions by *Trauger et al.* [1980], *Brown* [1981, 1982], and *Roesler et al.* [1982].

Acknowledgments. This work was supported by NASA under contract 953733 to MIT from the Jet Propulsion Laboratory.

The Editor thanks W. S. Kurth and G. L. Siscoe for their assistance in evaluating this paper.

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(Received September 4, 1984;
accepted October 4, 1984.)