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Possible in Situ Detection of K^{2+} in the Jovian Magnetosphere

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During the Voyager 1 and 2 encounters with Jupiter in 1979 the positive ion composition of the cold thermal plasma in the Jovian plasma sheet and cold Io torus could be obtained when the plasma Mach number in the spacecraft rest frame was sufficiently large. Clear indication of an ionic species with a mass-to-charge ratio between 16 (O^+ and/or S^{2+}) and 23 (Na^+) is present in two spectra, one from the Voyager 1 encounter and one from the Voyager 2 encounter. Both of these spectra were acquired during apparent crossings of the plasma sheet in the middle magnetosphere. One interpretation is that the most likely identification of the ion is K^{2+}, even though there is no evidence in the data for K^+. Such an ion presence would be consistent with reports of neutral potassium associated with the Jovian system and originating at Io as well as with the identification of an ion with a similar mass-to-charge ratio at higher energies in the Ulysses data. An alternative interpretation is that the ion is a singly ionized molecular species associated with water products sputtered from Europa, a scenario which may also be consistent with the Ulysses data. However, other species present in the data and the low temperatures favor the Iogenic potassium hypothesis.

INTRODUCTION

The encounter of the Voyager 1 spacecraft with Jupiter in March 1979 demonstrated that the magnetosphere of Jupiter is filled with a complex heavy-ion plasma. Determination of the composition of the low-energy thermal component (T_{ion} < 100 eV) measured in situ by Voyager relies upon the convective electric field of Jupiter providing a common bulk velocity to the ions that were measured by the Plasma Science (PLS) experiment.

As the PLS instrument is an electrostatic device [*Bridge et al.*, 1977], ions appear in the energy-per-charge spectra separated by mass per charge, provided that they enter with the same velocity and their effective Mach number (ratio of convective speed into a given cup of the PLS instrument to the ion thermal speed) is sufficiently large (see, for example, Appendix A of *McNutt et al.* [1981]). Along the Voyager trajectories, the magnetic field is typically about perpendicular to the cup normals, so most of the ion velocity is simply the convective $\mathbf{E} \times \mathbf{B}$ velocity in the magnetosphere, and differential field-aligned streaming velocities of ions with respect to each other are not an issue. A net potential on the spacecraft with respect to the surrounding plasma can also produce shifts that distort a true mass-per-charge separation of the ions. However, in the regions of the cold plasma sheet the temperature of the core electron population is ~10 eV, comparable to the ion temperatures. The associated potential of Voyager is then small compared with the convective energy of the positive ions into the PLS sensors [*McNutt et al.*, 1981; *Barnett and McNutt*, 1983], and any spacecraft potential produces negligible shifts in the position of the heavy-ion peaks in the energy-per-charge spectra.

By using the PLS ion data the mass-per-charge ratios of the major ions in the cold Io torus [*Bridge et al.*, 1979; *Bagenal and Sullivan*, 1981; *Bagenal*, 1985] and in the middle magnetosphere of Jupiter [*McNutt et al.* 1981; *Bagenal et al.*, 1992] were derived. Consistency arguments based on EUV spectra [e.g., *Shemansky and Smith*, 1981; *Bagenal*, 1989] and the observed mass-to-charge ratios (e.g., Appendix B of *McNutt et al.* [1981, and references therein]) have shown that the positive ions consist of H^+, Na^+, and a variety of sulfur and oxygen ions as well as SO_2^+ [*Bagenal and Sullivan*, 1981].

The observed high-ionization states of oxygen and sulfur, that is, O III (O^{2+}) and S IV (S^{3+}) are primarily created by the suprathermal electron population in the torus, as the thermal temperature is small compared with their ionization temperature [*Sittler and Strobel*, 1987]. Once created, these states are not greatly depleted; during the Voyager 1 encounter, significant amounts of ions with mass-to-charge ratios 8 and 32/3 with kinetic temperatures of ~10 eV were found in the middle magnetosphere (~10 R_J to ~40 R_J at crossings of the plasma sheet) [*McNutt et al.*, 1981; *Bagenal et al.*, 1992]. The mass-to-charge ratio of 8 could be a combination of O III and S V. However, the unique identification of the peak at 32/3 with S IV, the lack of a discernible peak at 16/3 (for O V), and the comparable ionization potentials of O II and S III (35.1 and 34.8 eV) and O III and S IV (54.9 and 47.3 eV) [*Allen*, 1973] all argue for little SV in the middle magnetosphere. In addition, the presence of O^{2+} and S^{3+} suggest that any other ions present in the Jovian system would have charge states consistent with ionization potentials of up to ~35 eV.

OBSERVATIONS

In surveying all of the high-resolution (M mode) spectral scans acquired at Jupiter, I have identified two energy-per-charge spectra from the Voyager PLS data, which indicate the presence of a magnetospheric ion with a mass-to-charge ratio between 16 (O^+/S^{2+}) and 23 (Na^+). The first spectrum was identified in the Voyager 1 data 41.3 R_J from Jupiter in the first inbound crossing of the cold plasma sheet by that spacecraft [*McNutt*, 1980]. The second was identified in Voyager 2 data acquired in a cold plasma sheet crossing near closest approach at 10.2 R_J [*McNutt*, 1982]. Features in a few other spectral scans may also contain the signature of this ion; however, a lack of clear definition of the peak (in Voyager 1 data) and the lack of simultaneous signatures of enough of the major ionic species to identify clearly the plasma convective velocity makes these identifications more problematic.

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Analysis of the Data

Fitting Procedure

In fitting the spectra referred to immediately above I have employed the damped least squares procedure [*Levenberg*, 1944; *Marquardt*, 1963] as modified by *Bevington* [1969] and employed previously in analyses of PLS data from the magnetospheres of the outer planets and the solar wind. The analysis incorporates the model response of *Barnett and Olbert* [1986] but does not include a fit to all of the data in the spectra. In both cases a still-unidentified warm plasma background and/or electron "feedthrough" contributes to the measured currents, and a successful simulation to the entire spectrum has not yet been obtained. However, the cold plasma is sufficiently concentrated in a few energy-per-charge channels that this omission is not critical to deriving fairly accurate parameters for the modeled parts of the distribution. Details of the fitting function and related caveats are given in the appendix.

As discussed in more detail in the appendix, the various ion species are here assumed to be well represented by convected isotropic Maxwellian distributions. A density, a component of convective velocity into the PLS side sensor, and a thermal speed are then fit for each of the components. Although a mass-to-charge-ratio is assumed for each species, it provides a normalization rather than an additional constraint in the the fitting process (see equation (A4) and the accompanying discussion). To the extent that spacecraft charging is negligible (not always the case as discussed below), the equality of the convective speeds for the various species then acts as a consistency check on the assumed mass-to-charge ratios. Despite the presence of low kinetic temperatures among the high-ionization state ion species observed by Voyager in the middle magnetosphere, the plasma is not in a state of thermodynamic equilibrium. *McNutt et al.* [1981] showed that neither equal thermal speeds or equal temperatures prevail for the cold ions, in contrast to the isothermal ions observed in the cold Io torus [*Bagenal and Sullivan*, 1981]. This basic result of lack of thermodynamic equilibrium is reproduced in the analysis reported on below and remains an outstanding problem of the energetics of the low-energy plasma.

Voyager 1: 41 R_J

The top row in Figure 1 shows the spectral scans taken with the Voyager 1 PLS side sensor (D cup) at 1020:47 and 1030:23 spacecraft event time (SCET) on day 62 of 1979. Voyager 1 was 41.3 R_J from Jupiter (inbound), and the corresponding rigid corotation speed was 518 km s^{-1} for the first scan and 41.2 R_J and 516 km s^{-1}, respectively, for the second scan.

These data are from the first crossing of the dense, cold plasma sheet identified by Voyager 1 [*McNutt et al.*, 1981]. The random measured currents in the lower half of the scan (channels 1 through ~80) indicate the instrumental noise level in this mode. Data obtained at this time from the three other sensors (not

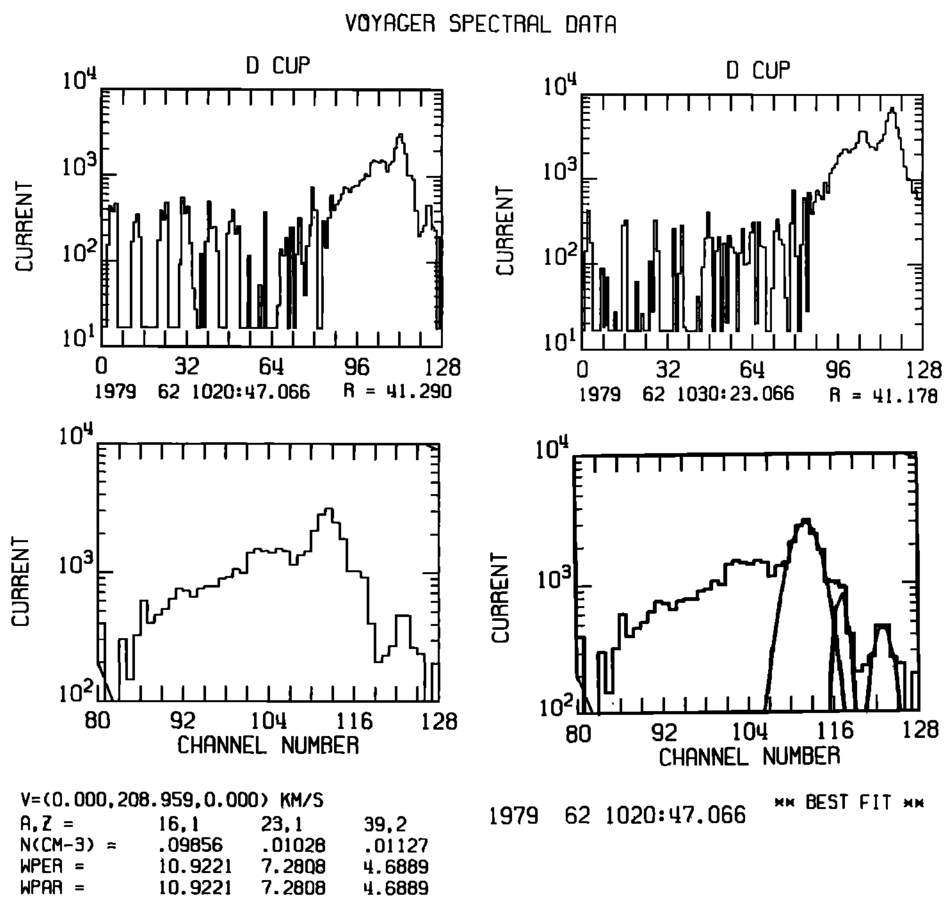

Fig. 1. Spectra and partial fits from ~41 R_J acquired by Voyager 1 on day 62 (March 3) of 1979. The top two panels show the full spectral scan from the high-resolution spectra taken with the PLS D cup. The lower two panels show a blowup of the spectrum to the left and a fit to the resolved parts of the data to the right. Unresolved pieces correspond to a combination of ions with mass-to-charge ratios of 8, 32/3, and others with higher temperatures.

shown) exhibit similar noise signatures throughout the entire scan.

The scan at 1020 SCET exhibits peaks consistent with mass-to-charge ratios of 16 and 23, an enhancement consistent with 32/3, and a shoulder at ~19 (assuming a common convective velocity and a spacecraft potential of zero volts with respect to the surrounding plasma). The scan 10 min later shows peaks consistent with ratios of 8, 10 2/3, and 16; the features near 19 and 23 are no longer obvious in this more typical spectrum (the low-resolution scan at this time shows a low-energy shoulder consistent with H^+, but a "good" set of fit parameters for the H^+ cannot be uniquely determined).

The second row in Figure 1 shows a blowup of channels 80 to 128 for the spectrum at 1020 along with a fit to the data utilizing the "full response" function of the instrument [*Barnett and Olbert*, 1986]. To the right, these data are reproduced along with a superimposed fit. Isotropic Maxwellian distributions convected in the azimuthal sense around the planet are assumed. To avoid problems with the unmodeled background (which can be modeled with populations of O^{2+} and S^{3+}, but not unambiguously), the fit is to channels 111 through 119 (16 and 39/2) and channels 122 through 125 (23). The fit parameters yield a good representation of the data, given the assumptions. The plot shows the azimuthal velocity component of the mass-to-charge 16 component as well as densities and thermal speeds for all three components assumed. Separate Maxwellians were actually fit to allow for an assessment of the assumed mass-to-charge ratio of 39/2 (this choice is discussed below) as well as an assessment of spacecraft charging effects. Also, one-sigma uncertainties in the fit parameters were determined by estimating the reduced chi square (χ^2) by the fit variance (see, for example, *Bevington* [1969]). The fit parameters and one-sigma uncertainties are shown in Table 1.

Uncertainties are large for the sodium peak as it does not yield a good fit to a Maxwellian (even with only four channels used). This makes it difficult to assess the effect of spacecraft charging on the assumed composition based upon these two peaks. By using the values from this fit a negative spacecraft potential of -356 V would be inferred from the O^+ and Na^+ signatures. This implies a true bulk speed into the cup of 198 km s^{-1} (equivalent to a streaming energy of 3.27 keV) and a "true" identification of the shoulder as having a mass-to-charge ratio of 18.6. However, a best fit to the ill-defined proton peak in the following low-resolution spectrum yields a positive potential. These results from postulating a spacecraft charge thus are limited by the noise associated with the low-flux levels in these spectra. Nearer Jupiter, *Barnett and McNutt* [1983] found that the Voyager 1 data were consistent with much lower spacecraft potentials, less than ~50 V in magnitude.

Because of the electrostatic nature of the PLS experiment, separation of the ~19 mass-to-charge peak from the 16 peak only occurs if the effective Mach number (ratio of convective speed into a PLS cup to the thermal speed) of the 16 peak is sufficiently high. The kinetic temperatures of the sample spectra are anomalously low in this regard, here <10 eV. These conditions are typically encountered when the electron temperature (of the core population) is comparable to the ion temperature. Such low electron temperatures also imply that the spacecraft potential is probably not an issue for the correct interpretation of these data.

The assumption of O^+ for the peak at 16 is an oversimplification, as part of the contribution to the signal is S^{2+} [*Bagenal*, 1985; *McNutt et al.*, 1981]. The assumption that the high-energy peak is Na^+ is based upon the known presence of sodium in the Jovian system [see *Sullivan and Bagenal*, 1979] and rough consistency in convective velocity with the peak at 16. The fit velocity components imply a mass-to-charge ratio of 23.8 ± 0.4 which is suggestive of Mg^+, but magnesium has not been identified spectroscopically in the Jovian magnetosphere while sodium has been. The assumption that the feature with a mass-to-charge ratio near 19 actually is K^{2+} is discussed in more detail below.

Voyager 2: 10 R_J

The Voyager 2 spectra Figure 2 are from the main sensor cups acquired by the Voyager 2 PLS experiment near its closest approach to Jupiter. At this time the azimuthally moving plasma flow is almost directly into the main sensor cluster (similar to the geometry encountered by Voyager 1 in moving through the cold Io torus). A subset of the data is shown along with best fits to the data in the individual cups in Figure 3; the corresponding fit parameters are given, along with formal one-sigma errors, in Tables 2 through 4. It is important to note that although the data were obtained simultaneously, the fit to the data in a given cup is made independently from the data in the other two cups. The data in the B and C cups are similar yet quite different in detail from the data in the A cup, for example, near the top of the largest peak in the scans. Fits based on isotropic Maxwellians and using the data in all three cups exhibit marked deviations from the data in at least one of the cups. Near this time the average magnetic field is most closely aligned with the normal into the B cup and even a bi-Maxwellian is incapable of resolving the discrepancies. A possible resolution to this observational problem might be that the magnetic field, and hence pitch angle distribution, was changing on the same timescale as the measurement (this implies time aliasing in the plasma data as well as noted below). A full study of the possibilities is beyond the scope of this paper.

The fits have been made assuming independent Maxwellian distributions of O^{2+} (8), S^{3+} (32/3), O^+ (16), H_2O^+ (18), and K^{2+} (39/2). In addition, there is an unmodeled (and unresolved) warm plasma background, which is typical of the spectra scans obtained by Voyager 2 in the middle magnetosphere; these spectra as well as those in the cold plasma sheet near it are quite anomalous [cf. *McNutt et al.*, 1981, Figure 20].

In going from one high-resolution spectral scan to the next (96 s) there are significant (sometimes factor of ~2) shifts in the measured current levels. Given the plasma convective speed of ~125

TABLE 1. Inferred Plasma Parameters at 1020 SCET, Day 62, 1979, Voyager 1 - PLS D Cup: Channels 111 - 119 and 122 - 125

Ion	Density, cm^{-3}	Convective Velocity, km s^{-1}	Thermal Speed, km s^{-1}	Temperature, eV
O^+	0.0986 ± 0.0032	208.96 ± 0.26	10.92 ± 0.37	9.96
K^{2+}	0.0113 ± 0.0021	207.76 ± 0.51	4.69 ± 0.43	4.48
Na^+	0.0103 ± 0.0025	212.04 ± 1.51	7.28 ± 2.74	6.36

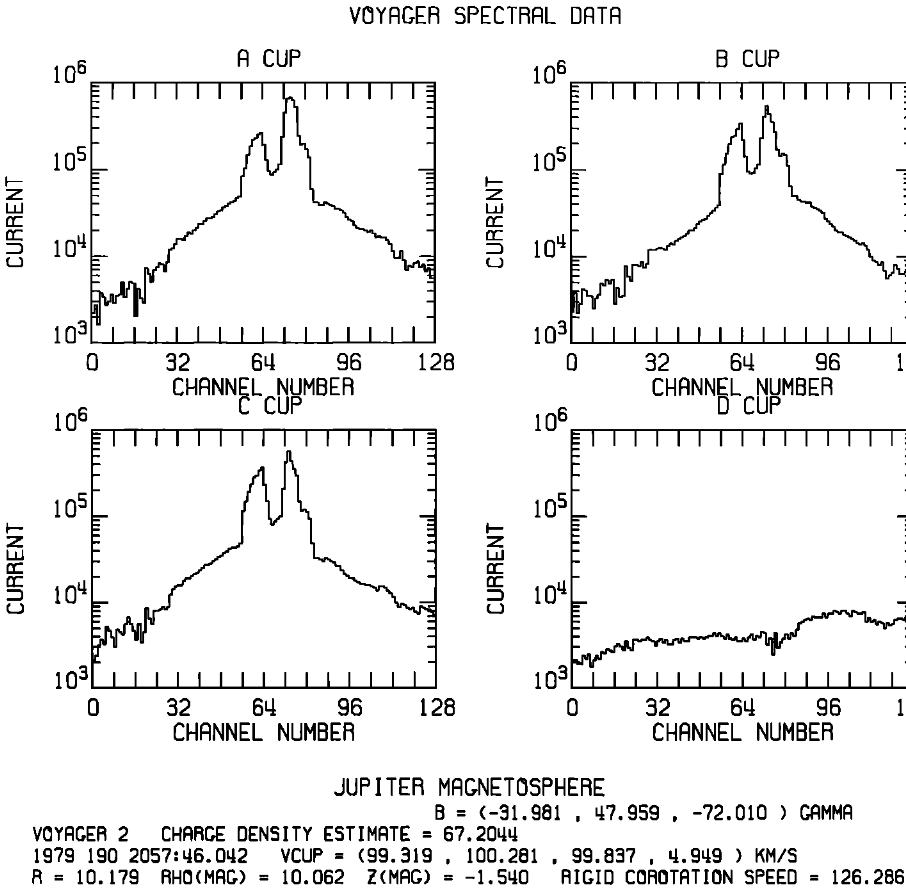

Fig. 2. Spectra acquired by Voyager 2 from ~10 R_J on day 190 of 1979 at 2057:46 spacecraft event time. These data were taken near closest approach to Jupiter. The scans are all from 10 to 5950 eV (convective energy into each of the cups of the Plasma Science experiment).

km s^{-1}, such changes correspond to density/composition/thermal gradients with scale lengths of ~0.2 R_J, and, since Voyager 2 is near periapsis at this time, such changes are most likely associated with azimuthal (rather than radial or latitudinal) plasma sheet structure. In other words, this observation may have resulted from the spacecraft encountering a parcel of plasma, rather than passing through a plasma sheet per se.

Features in the D cup spectrum of Figure 2, such as the "dip" around channel 72, suggest even smaller-scale length gradients, in turn giving rise to time-aliased features within these spectral scans themselves. This feature is ~10 channels wide; interpreted as spatial rather than velocity-space features, the data imply scale lengths of the order of 300 km ~0.004 R_J.

Returning to the main-sensor data, the lower-energy peak modeled with O^{2+} and S^{3+} actually starts at channel 57; data in channel 56 and below are from the previous scan, and the sharp onset may be an aliasing feature. In addition, the derived convective velocity components for these two species are quite different, and the data are, as an alternative, also consistent with a single species with mass-to-charge of 32/3 appearing to "cool" in the spacecraft reference frame as a blob of cold plasma is convected by Voyager. The S^{3+} and O^+ velocity components are essentially the same. For the assumed O^{2+} feature in the A cup to have a convective velocity component of 125.9 km s^{-1}, it would need to be an ionic species with a mass-to-charge ratio of 8.8.

One could argue that some of these problems are due to misidentification of the mass-to-charge ratios (there are no H^+ signatures in any of the plasma data acquired in this region by Voyager 2). However, the fit in the B cup yields a consistent speed of all components into the cup (except the species with mass-to-charge ratio of 8) of between 97.4 and 99.0 km s^{-1}. This compares favorably with a component expected from rigid corotation of 100.3 km s^{-1}; similar results hold for the other cups.

The inclusion of a species at mass-to-charge 18, for example, H_2O^+, suffices to provide a good fit to the data but could as easily (and likely) be either a non-Maxwellian feature on the 16 peak or time aliasing of the same. The purported K^{2+} feature actually shows a peak in all three cups. This is the only spectrum for which (1) there is a distinct peak near mass-to-charge ratio of 19 (for any data from either encounter), (2) there is a more dominant O^+ (mass-to-charge ratio = 16) feature present, and (3) the derived azimuthal speed is sufficiently close to rigid corotation that the species identification is plausible. The peak at 32/3 also has a consistent speed, but the feature on the low-energy side makes the identification somewhat problematic as discussed above.

In each of the cups the identification of the peak at mass-to-charge M/Q ratio of 16 as S^{2+} would bring the temperature more in line with those of the other plasma components.

It is also worth noting that in each of the cups the fit velocity component of (the assumed) K^{2+} is higher than that of the O^+. If the O^+ velocity components in the various cups are accepted as "correct," then the heavier component would have M/Q of 19.7 to 20.0, depending upon which cup is used for the calculation. These offsets could be due to (1) the unmodeled background, (2)

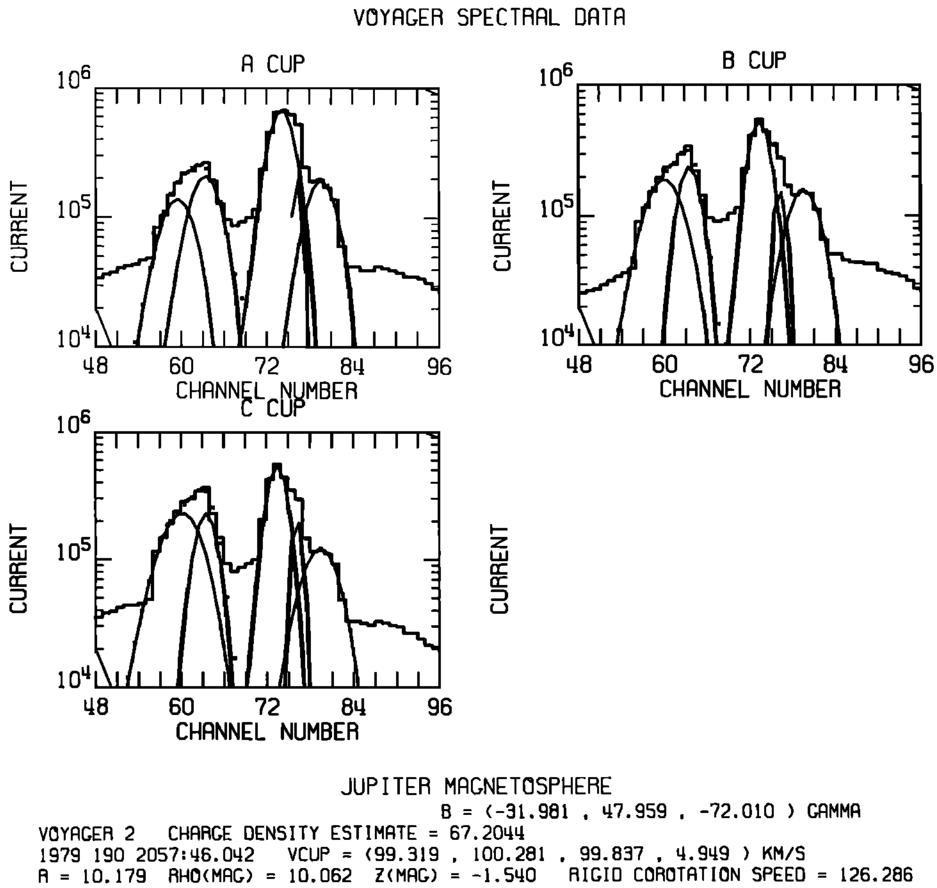

Fig. 3. Spectra and partial fits to the same spectral scans depicted in Figure 2. Only part of the full scan is shown along with superimposed fits to a subset of the data.

nonzero spacecraft potential, and/or (3) the inclusion of H_2O^+ in the fit. For comparison, the same procedure using the Voyager 1 data discussed previously (see Table 1) yields *M/Q* values of 19.13 to 19.42, again assuming no spacecraft potential (as well as having no actual peak).

Unlike the Voyager 1 observations, there is no evidence for Na^+ at comparable density levels in the Voyager 2 data. If the observed peak were really due to Na^+, the convective velocity would have to be lower by a factor of $(19.5/23)^{1/2}$, inconsistent with the largest peak having a mass-to-charge ratio of 16. Given the totally anomalous character of this spectrum, it is not clear what this implies (if anything) for the sodium and potassium sources. It does imply that the plasma density, temperature, and composition can be quite erratic as close as ~10 R_J to the center of Jupiter.

THE POTASSIUM HYPOTHESIS

The Case for Potassium

The original reasoning that led to a tentative identification of K^{2+} in the magnetosphere was [*McNutt*, 1980]: (1) there was clear evidence (see Figure 1) for an additional ionic species with a mass-to-charge ratio between 16 and 23, (2) such a mass-to-charge ratio was not possible with other ionic states of previously identified species, (3) neutral potassium had been identified in Jupiter's magnetosphere [*Trafton*, 1975, 1977], (4) the mass-to-charge ratio for doubly ionized potassium at 39/2 = 19.5 is nearly correct for the observed feature, and (5) the ionization potentials for K^{2+}, S^{3+}, and O^{2+} are comparable, so the presence of all of these ions is consistent with neutral sulfur, oxygen, and potassium having the same ionization / thermal history.

TABLE 2. Inferred Plasma Parameters at 2057 SCET, Day 190, 1979, Voyager 2 - PLS A Cup: Channels 57 - 66 and 72 - 83

Ion	Density, cm^{-3}	Convective Velocity, km s^{-1}	Thermal Speed, km s^{-1}	Temperature, eV
O^{2+}	3.8505 ± 1.3817	132.3068 ± 2.4188	6.8236 ± 3.4962	3.89
S^{3+}	3.8226 ± 0.9716	125.2385 ± 0.8184	5.7900 ± 0.7932	5.60
O^+	30.0487 ± 1.3290	125.9276 ± 0.1566	4.5781 ± 0.1934	1.75
H_2O^+	3.4675 ± 0.9530	124.3957 ± 0.1535	1.3991 ± 0.2963	0.18
K^{2+}	4.9771 ± 0.5295	126.4702 ± 0.4640	5.3311 ± 0.6182	5.78

TABLE 3. Inferred Plasma Parameters at 2057 SCET, Day 190, 1979, Voyager 2 - PLS B Cup: Channels 57 - 66 and 72 - 83

Ion	Density, cm^{-3}	Convective Velocity, km s^{-1}	Thermal Speed, km s^{-1}	Temperature, eV
O^{2+}	5.7631 ± 1.3810	132.6553 ± 1.4456	7.6631 ± 1.5318	4.90
S^{3+}	3.0244 ± 0.9740	124.9582 ± 0.4781	4.0739 ± 0.5334	2.77
O^{+}	19.8068 ± 1.4994	123.7146 ± 0.2191	3.8759 ± 0.3135	1.26
H_2O^{+}	3.4032 ± 1.7599	123.2102 ± 0.4673	2.0345 ± 0.6522	3.89
K^{2+}	4.3907 ± 0.9294	125.3786 ± 0.9915	5.8721 ± 1.3375	7.02

Subsequent to the presentation of this hypothesis, *Shemansky and Smith* [1981] noted that a combination of K III and S V gave a satisfactory explanation for some of the features observed in the EUV spectra of the Io torus. Their model is, at the least, a consistency check with the identification of K^{2+} in the in situ PLS data. From their analysis, any $M/Q = 8$ spectra in the PLS data would be ~3% Sv (S^{4+}) if the Io torus composition prevails in the middle magnetosphere [*Bagenal et al.*, 1992]. Such a fractionation is consistent with the nominal identification of the $M/Q = 8$ peak with O^{2+} rather than S^{4+} as was argued above, based on the ionizational potentials of the various sulfur and oxygen ions.

During a period of more work on the interpretation of the Jupiter data from Voyager the spectra shown in Figures 2 and 3 were found with the characteristic peak just above that at 16. It was reported that K^{2+} had probably been identified [*McNutt*, 1982], but that Ca^{2+} could not be ruled out (neutral calcium emission from Io at 422.7 nm was reported by *Mekler and Eviatar* [1974] but has never been confirmed). Also, at that time it was reported [*McNutt*, 1982] that in the spectral set following that of Figure 3 (192 s later), the plasma characteristics had changed to show an Na^+ signature. Closer examination (and more care) shows that the following spectrum may actually show S^+, although neither identification is unique; in any case the kinetic temperature of the plasma is higher and the mass-to-charge peak near ~19 is totally obscured.

There is no evidence for K^+ at a mass-to-charge ratio of 39 in any of the Voyager PLS data; however, this could partially be a selection effect as even the M/Q peaks at 23 (Na^+) and 32 (S^+) typically lie above the energy range of the instrument in the magnetosphere (to see a peak at a mass-to-charge ratio of 39, the convection speed into a cup must be less than 170 km s^{-1}). The ionization potential of neutral potassium is low (4.3 eV) and that for K^+ (31.6 eV) is lower than that of O^+ (35.1 eV) and S^{2+} (34.8 eV). Given the dominance of the mass-to-charge species at 16 (ionization potential of neutral oxygen 13.6 eV and of S^+ at 23.3 eV) [see *McNutt et al.*, 1981, Table 1] and the presence of O^{2+} and S^{3+} in the magnetosphere [*McNutt et al.*, 1981; *Bagenal et al.*, 1992] it is plausible (as noted above) that most of the ionized potassium present in the middle magnetosphere is in the doubly ionized state. In addition, when this signature is present, there are also present Na^+ and S^{3+} both of which are associated with an Io torus source.

In addition, the ionization potential for Na^+ and S^{3+} is ~47.3 eV and is greater than that for K^{2+} at 45.7 eV. Hence the presence of doubly ionized potassium is also consistent with a lack of Na^{2+} and S^{4+}.

Voyager data obtained at higher particle energies provide no corroborating evidence for potassium ions. *Vogt et al.* [1979] found only upper limits for potassium at energies of > 7 MeV per nucleon (their Figure 4 shows a small signature at Z=19.5, which is not statistically significant). At the same time, they did find energetic sodium to be enhanced by a factor of > ~270 with respect to solar system abundances.

The Possibility of Water Group Ions

An alternative explanation is that the ion is a water group ion with a mass to charge ratio of 17, 18, or 19 (H_nO^+, n = 1, 2, or 3) [*Schreier et al.*, this issue]. In this case the source is not Io but rather, most likely, water debris from Europa. *Lanzerotti et al.* [1978] considered the possibility that sputtered ions from water ice on the surfaces of the Galilean satellites could contribute significantly to the heavy-ion population of the Jovian magnetosphere. Depending on the species and concentrations present, the density of H_3O^+ can dominate that of H_2O^+ [*Aiken*, 1974] yielding a dominant signature with an M/Q of 19. However, as *Schreier et al.* [this issue] show conditions in the Jovian magnetosphere result in rapid recombination of H_3O^+ and about equal amounts of H_2O^+ and OH^+. Further, they find that these two species should have densities of no more than approximately one third that of either S^{3+} or Na^+, unlike what is actually observed. So, on the basis of density ratios with other species, the identification of the mass-to-charge peak of 19 with water group ions appears to be ruled out.

TABLE 4. Inferred Plasma Parameters at 2057 SCET, Day 190, 1979, Voyager 2 - PLS C Cup: Channels 57 - 66 and 72 - 83

Ion	Density, cm^{-3}	Convective Velocity, km s^{-1}	Thermal Speed, km s^{-1}	Temperature, eV
O^{2+}	7.5695 ± 1.4269	133.2154 ± 1.2294	8.3835 ± 1.3012	5.87
S^{3+}	2.9913± 0.9833	125.1967 ± 0.3888	4.1582 ± 0.5068	2.89
O^{+}	18.9990 ± 0.1962	124.1750 ± 0.1558	3.5205 ± 0.2318	1.04
H_2O^{+}	4.0990 ± 1.3775	123.5977 ± 0.2841	1.8095 ± 0.4445	0.31
K^{2+}	3.7278 ± 0.0168	125.4982 ± 1.3689	6.3391 ± 1.8091	8.18

The Voyager 2 observation tends to rule out Ganymede and Callisto as sources because they would have to provide inwardly diffusing ions that retain a low temperature rather than heating adiabatically. The more remote Voyager 1 observations could be consistent with all three outer Galilean satellites though.

If the signature observed by Voyager 2 is from water group ions associated with Europa, then the ions should originate with a thermal speed comparable to the local pickup speed. The implied temperature is on the order of ~1 keV (comparable to that of the hot background plasma discussed below). Relatively rapid transport times [see *Schreier et al.*, this issue] would remove the material from this region before it cooled to the observed temperature. Hence the temperature found from the Voyager 2 observation tends to rule out water group ions.

Finally, the Voyager observations would appear to favor slightly a mass-to-charge ratio of 19.5 (= 39/2) rather than 19. A mass-to-charge ratio of 17 or 18 is even less likely; however, given all of the uncertainties, this information of itself cannot be regarded as conclusive.

Ulysses Results

Results from the Ulysses flyby of Jupiter also suggest the presence of a minor ion with a mass-to-charge ratio of ~19. This ion is probably the same ion seen by Voyager and, again, may be K^{2+} [*Hamilton et al.*, 1992]. Unfortunately, the integrated counts at the higher energies sampled by the Solar Wind Ion Composition (SWICS) experiment [*Gloeckler et al.*, 1992] are small, and no triple coincidences have been identified at the time of this writing. Such triple coincidences in the instrument data set would unambiguously identify the charge state as +1 or +2 and would settle the potassium versus water group ion identification issue; work on this project is currently underway (D. C. Hamilton, private communication, 1992).

Implications of a "Hot" Background

The Jovian magnetospheric plasma sampled during the Voyager 2 flyby did not exhibit the regions of cooler, and therefore analyzable, plasma sampled by Voyager 1 [*McNutt et al.*, 1981]. It has been suggested that this difference may be due to the magnetosphere undergoing a compression during the dayside pass of Voyager 2 as compared with an expansion during the similar pass of Voyager 1 [*McNutt et al.*, 1987]. One is given the impression in looking at the data that the plasma during the Voyager 2 encounter was hotter; however, there has always been a question as to whether a hot background plasma was present in the Voyager 1 data but just at a relatively lower amplitude.

Much work done on the PLS data since the time of the Jupiter encounters has confirmed that there are sufficient quantities of hot electrons to cause a background feedthrough signal into the the positive ion data at some level [*Sittler and Strobel*, 1987; *McNutt*, 1988]. There is unquestionably an additional background signal, in addition to the cold ions, in the spectra of Figure 3. In fact, the background, without the cold ion peaks, is typical of the data returned by Voyager 2 during its closest approach to Jupiter. If the signals were only due to cross talk between the electron and ion modes of the instrument, then it would be similar in shape and amplitude in all four sensors, not just in the A, B, and C cups. Some of the signal is undoubtedly due to such an effect; however, it can be shown that the signals in all four sensors are consistent with a background heavy-ion plasma (M/Q ~8 to 16) with kinetic temperature of ~700 eV (thermal speed of ~90 km s^{-1}). Furthermore, the M/Q peaks for the O^+ and K^{2+} are near the peak of such a hot plasma distribution, so the fit parameters presented above are not significantly affected (I_k versus ϕ_k is relatively flat for the background in this region; see the Appendix).

It is beyond the scope of this paper to discuss the various trade-offs which can be made in fitting this background, for example, more species or non-Maxwellian features versus such a high kinetic temperature. What is significant is that this spectrum captures a snapshot of two different plasma distributions with entirely different thermal and therefore source and/or transport histories.

Evidence for a Europa Plasma Torus?

Intriligator and Miller [1982] identify an increase in the ion densities measured by Pioneer 10 near the time that spacecraft crossed the Europa L shell. They associated these enhancements with ion species consistent with water debris sputtered from the icy surface of Europa. They suggested that enhancements of the plasma density in data from Voyager 2 were also detections of plasma from a Europa source.

In the Voyager 2 data they referred to two density increases shown in Figure 7 of *McNutt et al.* [1981]. The first of these increases includes the spectra shown in Figures 2 and 3 of this paper (the maximum of the density increase they note is provided by this measurement). The presence of S^{3+} ions with a low kinetic temperature ~5 eV (see Tables 2 through 4) implies that the cold plasma population has its origins at Io, with subsequent ionization by relatively hot electrons, and then cooling from pickup energies on its way to this observation point outside the hot plasma torus. Their second identification in the Voyager 2 data is an enhancement of the hot plasma with no discrete peaks, so no conclusions based upon composition can be drawn.

The potassium hypothesis suggests that these density enhancements are Io-related and contrary to the suggestion of *Intriligator and Miller* [1982] are not a signature of a Europa plasma torus.

Similarly, there are no unique signatures of a Europa torus in any of the Voyager 1 PLS data. In the vicinity of Europa the plasma is sufficiently hot to obscure characteristic ion peaks in the spectral scans, and compositional changes that could be a torus signature are buried in a hot plasma background similar to that seen in the Voyager 2 data near closest approach (but see *Bagenal et al.* [1992] and *Schreier et al.* [this issue]).

SUMMARY AND CONCLUSIONS

To summarize, a minor ion species with a mass-to-charge ratio of ~19 has been identified in the Voyager 1 and 2 data acquired in the Jovian magnetosphere. The plasma conditions were especially suited to the detections, that is, high Mach number, in only two of positive ion spectra from both of the Voyager encounters. As a result, there is no information on the spatial distribution of this species. Although the mass-to-charge ratio cannot be determined from Voyager data to sufficient precision to rule out Ca^+, observations of neutral potassium favor the ion being K^{2+} if it originates near Io. Such an origin is suggested by the simultaneous presence of other Io-associated ions in the same spectral scans, namely S^{3+} and Na^+. If the ion species is K^{2+}, the kinetic temperature is low but comparable to those of the other cold ions present. In addition, the ionization state is consistent with the presence of S^{3+} and O^{2+} and the lack of sulfur and oxygen ions in the next higher ionization state.

The simultaneous presence of both hot and cold heavy-ion populations in the Voyager 2 data (associated with one of the K^{2+} observations) implies two different thermal histories. The observations also imply different transport histories and/or origins. The hotter material could be "more locally," that is, in a different location, picked-up from the ionization of neutral material. In this case the different component temperatures could just be due to different adiabatic cooling histories and/or collision rates. The apparent upper limit to the thermal speed of the hot material is in excess of Io's orbital speed and could suggest pickup remote from Io and/or other energization processes. At the very least these observations reveal that a single scenario of ionization near Io's orbit and transport outward is not consistent with the Voyager data.

If the ions with M/Q ~19 are singly ionized then the likely identification is water group molecules from the vicinity of Europa. Although a mass-to-charge ratio of ~19 ion has been identified in the SWICS data from Ulysses, the count rates are so low that it has not been possible to determine the charge state or the spatial distribution (integration of the count rates over most of the magnetospheric pass was required to obtain a significant signal)(D. C. Hamilton, private communication, 1992). Even though the ions detected with the SWICS are at a higher energy than those detected by Voyager, it is likely that the species is the same, given the presence of other kinetically hot ions of high ionization states found in the SWICS data. If Europa is the source, then one must account for either a large shielding electric field in the pickup region or an anomalously rapid cooling between Europa and the observation point.

Unless there is conclusive evidence found for the M/Q ~19 ions to be singly ionized, then the bulk of the current observational data (such as it is) favors the identification of the signatures as K^{2+} associated with the Io plasma source.

APPENDIX: OPERATION OF THE PLS INSTRUMENT

The Plasma Science instrument consists of four modulated-grid Faraday cups of a type used for interplanetary plasma measurements since the early 1960s [see *Vasyliunas*, 1971]. The basic operation of the PLS instrument is described by *Bridge et al.* [1977], and special characteristics of the operational mode during the encounters with Jupiter are described in detail by *McNutt et al.* [1981], *Bagenal and Sullivan* [1981], and *Scudder et al.* [1981]. The detailed effects of grid transparency, refraction of particle trajectories within the cup [see *Vasyliunas*, 1971], and collection inefficiency have been modeled for the main PLS sensor (the A, B, and C Faraday cups) by *Barnett and Olbert* [1986] and by *Barnett* [1984] for the side sensor (D cup). This model of the "response function" R has been employed with great success in analyzing data from the Io flux tube passage [*Barnett*, 1986], the magnetosphere of Saturn [*Richardson*, 1986], the middle magnetosphere of Jupiter [*McNutt et al.*, 1987; *Sands and McNutt*, 1988], the magnetosphere of Uranus [*Selesnick and McNutt*, 1987], and the magnetosphere of Neptune [*Richardson et al.*, 1991; *Szabo et al.*, 1991].

Each PLS cup can be thought of as a linear operator, which when applied to a distribution function f_a (v) of species a, produces a current $I_{k,a}$ in the kth energy-per-charge channel which is then encoded into the spacecraft telemetry stream. The current measured in the kth energy-per-charge channel due to an isotropic Maxwellian distribution of ions of charge Z^* and mass $A\, m_p$ (m_p being the mass of a proton) is given by

$$I_k = I_k^* - I_{k+1}^* \qquad \text{(A1)}$$

$$I_k^* = Z^* e \int_{v_k}^{\infty} v_z\, dv_z \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} d^2v_t\, f(\mathbf{v})\, R(v_k, \mathbf{v}) \qquad \text{(A2a)}$$

where the response function R has units of area and v_k is defined by

$$v_k = \sqrt{\frac{2e}{m_p}\frac{Z^*}{A}\,\phi_k} \qquad \text{(A2b)}$$

where ϕ_k is the modulator grid potential at the "bottom" of channel k, and the z axis is along the cup normal. For the Voyager PLS instrument the modulator potentials are, in turn, given by [*Bridge et al.*, 1977]

$$\phi_k = \phi_0\, 10^{\frac{k-1}{m}} - \phi_{\text{offset}} \qquad \text{(A2c)}$$

with ϕ_0 = 60 V and ϕ_{offset} = 50 V (the offset allows for both low- and high-energy ions and electrons to be detected while driving the step voltages over only two decades. Here k is the channel number and refers to the potential at the lower edge of the channel. For the high-resolution ion spectra (M mode) the constant m = 64 and k ranges from 1 to 128; for low-resolution ion spectra (L mode) m = 8 and k ranges from 1 to 16 (for the electron modes of the instrument, called E1 and E2 and only implemented in the D cup, k again ranges from 1 to 16, and m is 32 and 8 respectively; the sign of ϕ_k is, of course reversed from the ion modes, Z^* = -1 and A = 1/1836).

Note that (A1) can be rewritten as

$$I_k = Z^* e\left[\int_{v_k}^{v_{k+1}} v_z dv_z \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} d^2v_t\, f(\mathbf{v})\, R(v_k, \mathbf{v})\right]$$

$$+ Z^* e\left[\int_{v_{k+1}}^{\infty} v_z dv_z \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} d^2v_t\, f(\mathbf{v})\,[\,R(v_k, \mathbf{v}) - R(v_{k+1}, \mathbf{v})\,]\right] \qquad \text{(A3)}$$

which separates the current into the differential part (the first term) and the feedthrough contribution (the second term). The latter tends to skew the distribution of measured currents to lower energies with respect to the distribution function and gives a significant contribution to the measurements if the plasma is hot. As the ratio of thermal speed to normal velocity component decreases to small values (as in the solar wind), the second term becomes arbitrarily small, and the differential nature of the measurements is regained. If v_k is imaginary, which occurs if, for example, electrons are considered in the positive ion mode, then it can be shown that the differential term vanishes, but the feedthrough term still gives a contribution where the lower limit on the integral is now zero (all particle of the "wrong" sign can get into the sensor) but R is evaluated with $-v_k^2$ instead of v_k^2 wherever the latter appears in the expression for R [*Barnett*, 1984; *Barnett and Olbert*, 1986].

The ambiguity in the model parameters (density, thermal speed, and convective velocity) is made apparent by first noting that the response R is a function of v_z^2 / v_k^2 and $v_{t_1}^2 / v_z^2$ and is therefore independent of the mass-to-charge ratio of the ions (as it must be). Introducing the quantity $\phi_i \equiv A m_p v_i^2 / 2Z^* e$ with i representing x, y, or z, and assuming a Maxwellian distribution convected with velocity **V**, we obtain

$$I_k^* = \frac{e^2}{m_p\sqrt{\pi}}\left(\frac{Z^{*2}}{A}\,\frac{n}{w}\right)\int_{\phi_k}^{\infty} d\phi_z\, e^{-\frac{\left(\sqrt{\frac{2e}{m}\phi_z} - \sqrt{\frac{A}{Z^*}}V_z\right)^2}{A/Z^*\, w^2}}\,\bar{R} \qquad \text{(A4)}$$

where $\bar{R}$ includes the transverse integrations and is only dependent upon $\sqrt{A/Z^*}\,V_t$ and $\sqrt{A/Z^*}\,w$. Here n is the density and w is the thermal speed, related to the temperature T by $Am_p w^2/2 \equiv kT$.

It is readily apparent from (A4) that the model parameters for a given Maxwellian are actually $Z^* n\sqrt{Z^*/A}$, $\sqrt{A/Z^*}\,w$, and $\sqrt{A/Z^*}\,V$. Thus the fit parameters can be found from a best fit to the data combined with assumed values of the mass and charge of the ions. In the cold plasma sheet data in the middle Jovian magnetosphere [*McNutt et al.*, 1981] and in the cold Io torus [*Bagenal and Sullivan*, 1981; *Bagenal*, 1985] peaks in I_k versus k corresponding to ions of differing mass-to-charge ratios are well resolved in the PLS data, and the assumption of a common convective velocity, combined with fits to the data, yields values of A and Z^* consistent with (1) rigid corotation in the cold torus and (2) species identified on the basis of their UV spectral signatures in the warm Io torus [*Bagenal*, 1989].

In the warm torus as well as in regions outside the cold plasma sheet there is no resolution of the various ion species: information about the mass-to-charge ratios of different species is obscured by the large thermal speeds and non-Maxwellian tails of the observed distributions. The formulation just given can still be used to analyze the data, but the results are now in the form of a model based upon a non-unique parameterization of the in situ plasma and its assumed composition. Hence, even in regions where the plasma is "hot," one can still test null hypotheses and bracket plasma parameters [see *Bagenal*, 1989].

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REFERENCES

Aikin, A. C., Cometary coma ions, *Astrophys. J.*, *193*, 263-264, 1974.

Allen, C. W., Ionization potentials, section 16 in *Astrophysical Quantities*, 3rd ed., London, The Athlone Press, 1973.

Bagenal, F., Plasma conditions inside Io's orbit: Voyager measurements, *J. Geophys. Res.*, *90*, 311-324, 1985.

Bagenal, F., Torus-magnetosphere coupling, Time-Variable Phenomena in the Jovian System, chap. 16, edited by M. J. S. Belton, R. A. West, and J. Rahe, *NASA Spec. Publ.*, 494, 196-210, 1989.

Bagenal, F., and J. D. Sullivan, Direct plasma measurements in the Io torus and inner magnetosphere of Jupiter, *J. Geophys. Res.*, *86*, 8447-8466, 1981.

Bagenal, F., D. E. Shemansky, R. L. McNutt, Jr., R. Schrier, and A. Eviatar, The abundance of O^{++} in the Jovian magnetosphere, *Geophys. Res. Lett.*, *19*, 79-82, 1992.

Barnett, A., The response function of the Voyager plasma science experiment, *Tech. Rep. CSR-TR-84-1*, Cent. for Space Res., Mass. Inst. of Technol., Cambridge, 1984.

Barnett, A., In situ measurements of the plasma bulk velocity near the Io flux tube, *J. Geophys. Res.*, *91*, 3011–3019, 1986.

Barnett, A., and R. L. McNutt, Jr., Charging effects observed on Voyager 1 near Jupiter, 17th ESLAB Symposium on Spacecraft/Plasma Interactions and Their Influence on Field and Particle Measurements, *Eur. Space Agency Spec. Publ.*, *ESA SP-198*, 47-50, 1983.

Barnett, A., and S. Olbert, The response function of modulator grid Faraday cup plasma instruments, *Rev. Sci. Instrum.*, *57*, 2432-2440, 1986.

Bevington, P. R., *Data Reduction and Error Analysis for the Physical Sciences*, McGraw-Hill, New York, 1969.

Bridge, H. S., J. W. Belcher, R. J. Butler, A. J. Lazarus, A. M. Mavretic, J. D. Sullivan, G. L. Siscoe, and V. M. Vasyliunas, The plasma experiment on the 1977 Voyager mission, *Space Sci. Rev.*, *21*, 259-287, 1977.

Bridge, H. S., et al., Plasma observations near Jupiter: Initial results from Voyager 1, *Science*, *204*, 47, 1979.

Gloeckler, G., et al., The solar wind ion composition spectrometer, *Astron. Astrophys. Suppl. Ser.*, *92*, 267-289, 1992.

Hamilton, D. C., G. Gloeckler, A. B. Galvin, J. Geiss, and R. von Steiger, The charge state of oxygen ions observed in the magnetosphere of Jupiter with SWICS on Ulysses, *Eos Trans. AGU*, *73* (14), Spring Meeting Suppl., 181, 1992.

Intriligator, D. S., and W. D. Miller, First evidence for a Europa plasma torus, *J. Geophys. Res.*, *87*, 8081-8090, 1982.

Lanzerotti, L. J., W. L. Brown, J. M. Poate, and W. M. Augustyniak, On the contribution of water products from Galilean satellites to the Jovian magnetosphere, *Geophys. Res. Lett.*, *5*, 155-158, 1978.

Levenberg, K., A method for the solution of certain non-linear problems in least squares, *Q. Appl. Math.*, *2*, 164-168, 1944.

Marquardt, D. W., An algorithm for least-squares estimation of nonlinear parameters, *J. Soc. Ind. Appl. Math.*, *11*, 431-441, 1963.

Mekler, Yu., and A. Eviatar, Spectroscopic observations of Io, *Astrophys. J. Lett.*, *193*, L151-L152, 1974.

McNutt, R. L., Jr., The dynamics of the low energy plasma in the Jovian magnetosphere, Ph.D. thesis, Dep. of Phys., Mass. Inst. of Technol., Cambridge, 1980.

McNutt, R. L., Possible in situ detection of K^{2+} in the Jovian magnetosphere, *Eos Trans. AGU*, *63*, 1062, 1982.

McNutt, R. L., Jr., Net current measurements and secondary electron emission characteristics of the Voyager Plasma Science Experiment and their impact on data interpretation, *Tech. Rep. CSR-TR-88-6*, Cent. for Space Res., Mass. Inst. of Technol., Cambridge, 1988.

McNutt, R. L., Jr., J. W. Belcher, and H. S. Bridge, Positive ion observations in the middle magnetosphere of Jupiter, *J. Geophys. Res.*, *86*, 8319–8342, 1981.

McNutt, R. L. Jr., P. S. Coppi, R. S. Selesnick, and B. Coppi, Plasma depletions in the Jovian magnetosphere: Evidence of transport and solar wind interaction, *J. Geophys. Res.*, *92*, 4377-4398, 1987.

Richardson, J. D., Thermal ions at Saturn: Plasma parameters and implications, *J. Geophys. Res.*, *91*, 1381-1389, 1986.

Richardson, J. D., J. W. Belcher, M. Zhang, and R. L. McNutt, Jr., Low-energy ions near Neptune, *J. Geophys. Res.*, *96*, 18,993-19,011, 1991.

Sands, M. R., and R. L. McNutt, Jr., Plasma bulk flow in Jupiter's dayside middle magnetosphere, *J. Geophys. Res.*, *93*, 8502-8518, 1988.

Schrier, R., A. Eviatar, V. M. Vasyliunas, and J. D. Richardson, Modeling the Europa plasma torus, *J. Geophys. Res.*, this issue.

Scudder, J. D., E. C. Sittler, Jr., and H. S. Bridge, A survey of the plasma electron environment of Jupiter: A view from Voyager, *J. Geophys. Res.*, *86*, 8157-8179, 1981.

Selesnick, R. S., and R. L. McNutt, Jr., Voyager 2 plasma ion observations in the magnetosphere of Uranus, *J. Geophys. Res.*, *92*, 15,249-15,262, 1987.

Shemansky, D. E., and G. R. Smith, The Voyager 1 EUV spectrum of the Io plasma torus, *J. Geophys. Res.*, *86*, 9179-9192, 1981.

Sittler, E. C., and D. F. Strobel, Io plasma torus electrons: Voyager 1, *J. Geophys. Res.*, *92*, 5741-5762, 1987.

Sullivan, J. D., and F. Bagenal, In situ identification of various ionic species in Jupiter's magnetosphere, *Nature*, *280*, 798-799, 1979.

Szabo, A., G. L. Siscoe, A., A. J. Lazarus, R. L. McNutt, Jr., R. P. Lepping, and N. F. Ness, Magnetopause and cusp observations at Neptune, *J. Geophys. Res.*, *96*, 19,149-19,152, 1991.

Trafton, L., Detection of a potassium cloud near Io, *Nature*, *258*, 690-692, 1975.

Trafton, L., Periodic variations in Io's sodium and potassium clouds, *Astrophys. J.*, *215*, 960-970, 1977.

Vasyliunas, V. M., Deep space plasma measurements, *Meth. Exp. Phys.*, *9B*, 49-88, 1971.

Vogt, R. E., et al., Voyager 1: Energetic ions and electrons in the Jovian magnetosphere, *Science*, *204*, 1003-1007, 1979.

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