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First Evidence for a Europa Plasma Torus

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This paper summarizes the evidence from the Pioneer 10 plasma analyzer that plasma derived from Europa was present in the Jovian magnetosphere in December 1973. Plasma detected between 1900 UT and 2100 UT on December 3, 1973, shows a number of significant phenomena near the expected position of Europa's L shell. Mass addition to the magnetospheric plasma is suggested by a local increase in density apparently superimposed on the density gradient of Iogenic plasma. This increase in plasma density is unlike any phenomenon observed when the spacecraft is not close to a lunar L shell. The density shows fluctuations which allow an estimate of the net outflow speed of magnetospheric ions per Jovian rotation. We estimate a radial flow speed in 1973 of 0.37 km/s from the Pioneer data and we estimate 1 km/s in 1979 from Voyager 2 data, thus indicating a significant change. The mass addition from Europa is consistent with the expected derivation of oxygen ions (or OH^+ or H_2O^+) from the icy surface of Europa by sputtering or other processes or with the derivation of recycled sulphur ions from Europa. Evidence from other peaks in the plasma spectra also argues for the identification of the most prominent peak in these spectra as having M/Q in the range of 16–18. The estimate of the bulk plasma speed obtained by combining this identification with the absolute energies of the peaks and the spacecraft trajectory information indicates that at this time the corotation speed is substantially higher than the expected corotation speed for a large number of spectra. If the most prominent peak in the spectra were associated with M/Q values of 32, then the corotation speed would be consistent with rigid corotation. These results contrast with the Voyager 1979 observations and are more evidence for a large change in magnetospheric conditions between the 1973 and 1979 observations. We can account partially for the increased corotation speed of the plasma during the Pioneer 10 encounter by use of momentum conservation and compression of the magnetosphere by the solar wind.

INTRODUCTION

Recently, we reported that during the inbound passage of the Pioneer 10 flyby of Jupiter in December 1973, the Pioneer 10 plasma analyzer detected corotating plasma ions in the Io torus [*Intriligator and Miller*, 1981]. On this pass the outer collectors of the Pioneer plasma analyzer were close enough to the direction of corotation to observe the cold plasmas of the inner magnetosphere. In the present paper we report observations made by the Pioneer 10 plasma analyzer at larger distances extending well outside the Io torus. We describe observations of corotating plasma ions apparently associated with Europa. As in the case of our earlier paper, these plasma ions are detected in data from detector B, the medium resolution analyzer, not previously studied by others. We compare them with Voyager results and with UV observations of sulphur deposits on the upstream hemisphere of Europa.

The ion spectra presented in this paper show evidence of a significant composition change near the expected crossing of Europa's L shell. Analysis of the composition change, as described below, suggests that a portion of the plasma in this region is derived from Europa. This interpretation appears to be more plausible than the obvious alternatives, and it is consistent with laboratory data on sputtering of matter from icy surfaces.

The ion spectra indicate that the severe lagging behind corotation reported by the Voyager experimenters was not present in this region during the Pioneer 10 encounter representing a significant temporal change during the more than 5 years between the Pioneer and Voyager observations. These results are obtained by a model-independent comparison of the energies of various peaks in the measured ion spectra, as used by *Belcher et al.* [1980]. The higher observed speeds imply that the degree of mass loading (hence, presumably, the outflow speed) is less in the magnetosphere in December 1973 than it was during the Voyager encounter. This result is strengthened by the observation of periodic changes in the detected ions which appear to represent plasma streams from Europa entrained at successive Jovian rotations. An estimate can thus be derived of the mean outflow speed per Jovian rotation, using the Europa plasma as a 'tracer.'

While the interpretations of the Voyager plasma data published to date do not include identification of plasma from Europa, we will describe how these data appear to indicate the possible presence of the Europa plasma stream. The outflow speed we estimate from the published Voyager data is significantly higher than our Pioneer outflow speed estimate, confirming the inference from our corotation measurements that conditions were different during the two encounters. Both our Pioneer and Voyager estimates fall within the range used in theoretical calculations.

These observations imply that the Jovian magnetosphere can undergo large-scale and long-term changes. During the Pioneer 10 encounter the magnetosphere was in more of a 'quiescent state,' whereas in 1979 the Voyager spacecraft observed it in a more 'excited state.' The two observed states appear to be quite different from each other. At this point we have no way to know whether they are sharply separated or whether intermediate states are possible.

If the Europa ions observed by Pioneer are derived from water, then the observed bulk speed is greater than would be

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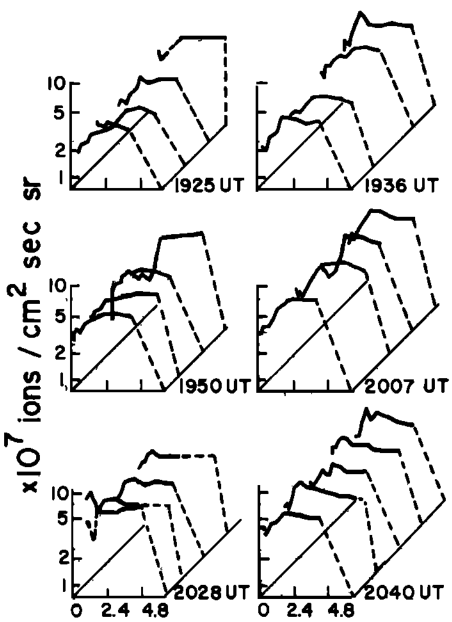

Fig. 1. Ion energy per unit charge (E/Q) spectra measured at Pioneer 10 in the vicinity of the Galilean moon Europa during the spacecraft's inbound trajectory on December 3, 1973. The ion spectra shown were obtained on an outer collector (collector 5) of detector B, the plasma analyzer with five current collectors. The ordinates indicate the ion intensity on collector 5. The E/Q range (the abscissas) of all these detector B ion spectra is from 100 V to 4.8 kV. The only data included are from portions of the energy scan which show evidence of corotating particles. Solid lines connect measurements which are in adjacent energy steps; dashed lines connect points which are not adjacent.

expected assuming strict corotation. We present a tentative explanation based on conservation of angular momentum and the compression of the outer magnetosphere on the dayside by the solar wind, which accounts quantitatively for some of the observed speed excess. The possible evidence of strong compression in our data corresponds generally with Voyager observations of strong flow away from the centrifugal equator on the dayside and may also support magnetohydrodynamic calculations of compression of the Jovian magnetosphere by a corotating interaction region at this time.

Smith et al. [1981] describe numerical simulations of the propagation of solar wind structures from Pioneer 11 to Pioneer 10 which provide quite accurate estimates of the low-frequency structure of the solar wind parameters before and after the Pioneer 10 Jupiter encounter. Their estimates appear reliable for the solar wind environment at Jupiter during the encounter while the spacecraft is immersed in the magnetosphere. They calculate that during this time the magnetosphere was still within a corotating interaction region (CIR), with a dynamic pressure around 10^{-9} dyn/cm^2. During the preceding two days the pressure had been as high as 4×10^{-9} dyn/cm^2, while the typical value during a rarefaction region was a few times 10^{-10} dyn/cm^2. Thus the magnetosphere was under relatively high dynamic pressure. To the extent that these effects propagated inward to the region of relatively strong magnetic field where our observations were made, they also may have contributed to phenomena we observed.

If the Europa ions observed by Pioneer are derived from recycled sulphur [*Lane et al.*, 1981], then the observed bulk speed is consistent with that expected assuming strict corotation. In this case, however, there also appear to be other ions present at unexpected mass/charge ratios.

Along with differences in the Pioneer and Voyager UV observations [*Broadfoot et al.*, 1979] and long-term drifts in the properties of the decimetric emission [*Hide and Stannard*, 1976] our results indicate the existence of long-term and large-scale changes in the Jovian magnetosphere. The Jovian magnetosphere was in a different state in 1973 than it was in 1979.

OBSERVATIONS

A description of the Pioneer 10 plasma analyzer and the orientation of its field of view in the middle Jovian magnetosphere is given in the work of *Intriligator and Miller* [1981]. The fields of view of the outer collectors (collectors 1 and 5) of detector B (the medium-resolution analyzer) and channeltrons 1 and 26 of detector A (the high-resolution analyzer) are closest to the direction expected for strict corotation. A plasma distribution would need to have a high temperature or a radial component of bulk motion or both for a significant part of it to be included in these fields of view [*Intriligator and Miller*, 1981]. During the period from ~1500 UT to 2055 UT (GRT—ground received time) on December 3, 1973, the Pioneer 10 plasma analyzer detected evidence of corotating ions over most of its energy range.

In the present paper we primarily discuss the data from detector B between 1925 UT and 2046 UT. A data gap from 2100 UT to 2200 UT separates these data from the Io torus spectra presented by *Intriligator and Miller* [1981]. During the period covered the effects of energetic particles on detector B were negligible.

Plasma Enhancements

Figure 1 shows ion energy per unit charge (E/Q) spectra of corotating ions in the vicinity of Europa in chronological order and in order of decreasing radial distance. These ions were detected on collector 5. Similar results were obtained from the other outer collector (1). Each spectrum in the figure shows data from only the portions of the energy scan which show evidence of corotating particles (i.e., higher currents when collector 5 was near the direction of corotation than when it was not; consistency of direction of detection was also important in the data selection). Solid lines connect measurements which are in adjacent energy steps, dashed lines connect points which are not adjacent.

According to the D3 model, the Europa L shell crossing occurred at 2026 UT [*Kivelson and Winge*, 1976]. A cursory comparison of the spectra in Figure 1 indicates that in the vicinity of Europa, particularly between 1958 UT and 2018 UT, they are relatively steady in energy and shape. However, careful examination indicates that the spectra measured before the L shell crossing have a number of significant differences from those obtained afterward: after the L shell crossing the peak flux is lower in each spectrum and the intensity of the peak at ~1100 V is more frequently comparable to the intensity of the principal peak or shoulder at ~1600 V. These characteristics suggest that both density and composition changes occurred around the time of the L shell crossing.

Figure 2 provides additional information concerning these changes. The upper top shows the peak collector ion intensity in the E/Q range from 1500 to 2100 V (the E/Q range of the most prominent peak in the spectrum) as a function of time. This graph provides strong evidence for a relatively localized intensity enhancement superimposed on an overall intensity gradient.

The bottom panel in Figure 2 shows the corresponding peak intensity for ions in the E/Q range of 2900–4100 V, representing twice the M/Q ratio of the ions in the top panel if the corotation speeds are approximately equal for both ions. Evidently the peak intensity variations in this E/Q range are not exactly the same but are quite similar to those in the lower E/Q range shown in the top panel.

The apparent intensity enhancement in the specific E/Q ranges associated with the observations in Figure 2 appears to be strong evidence of the spacecraft's passage through a distinct plasma population. The natural hypothesis that Europa might be the ultimate source of some of this plasma is strengthened by the evidence in Figure 2 that the plasma enhancement is only found outward from the Europa L shell. This is the expected location, since the Europa plasma would be carried outward by the outflow from the Io torus.

Corotation Speed

The plan of this section is first to discuss the corotation speed assuming that the Europa ions are water derived and then to disuss the alternative situation where the Europa ions are recycled sulphur from the ambient plasma. In the former case the corotation speed is higher than that expected for rigid corotation, and in the latter case it is consistent with that expected for rigid corotation. In either case the corotation speed in 1973 was considerably higher than the corotation speeds present in this region in 1979 as observed by Voyager.

The surface of Europa appears to be largely pure water ice. Heavy ions emitted from the surface might be expected to be predominantly fragmentation products of water—O^+, OH^+, or H_2O^+ and perhaps O_2^+—since the formation of other species would require more complex chemical reac-

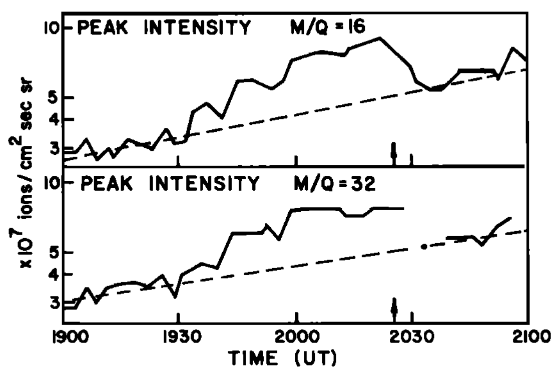

Fig. 2. Radial profiles of peak ion intensity in the vicinity of Europa during the Pioneer 10 passage in 1973. (Top) Radial profile of the peak ion intensity associated with M/Q = 16 in the vicinity of Europa. (Bottom) Similar plot for M/Q = 32. The peak ion intensity provides a rough estimate of the relative variation of the ion density. The small arrows at 2026 UT indicate the predicted time of crossing of the Europa L shell based on the D3 model of the magnetosphere [*Kivelson and Winge*, 1976]. The dashed lines suggest that from about 1930 UT to 2030 UT water-derived ions from Europa are superimposed on a smoothly varying background population of ions with M/Q = 16 and 32, respectively, presumably from the Io plasma torus. The text describes why the alternative identification of M/Q = 32 and 64 seems less probable.

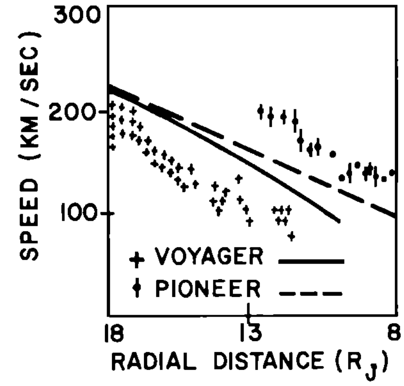

Fig. 3. Comparison between the Pioneer 10 and Voyager 1 [*McNutt et al.*, 1979] rigid corotation speeds in the middle magnetosphere. The Pioneer 10 (December 1973) measured corotation speeds including standard deviations are shown by the dots above the line. The Voyager 1 (March 1979) measured corotation speeds are shown by the crosses below the line. The dashed line indicates the expected magnitude of the rigid corotation speed at Pioneer 10. The solid line indicates the expected component of rigid corotation speed into the Voyager D cup. The data indicate that the plasma speeds in December 1973 and March 1979 are different, with the Pioneer speeds exceeding those predicted for rigid corotation and the Voyager speeds lagging the predicted speeds. A possible theoretical explanation for the difference between Pioneer and Voyager is discussed in the text. The less probable identification of the principal peak measured by Pioneer as M/Q = 32 would reduce the Pioneer speeds by 30% making them match the dashed line more closely.

tions. This indicates that the principal peak or shoulder at ~1500–2000 V represents M/Q values in the range 16–18. The implication is then that the kinetic bulk speed is above 127 km/s, in contrast to the expected corotation speeds during this period which range downward from 115 to 100 km/s. Thus the identification of the ions as O^+, OH^+, or H_2O^+ (species which could not be distinguished at the resolution of the instrument configuration at this time) implies plasma motion at this time faster than that expected for strict corotation. This result is significantly different from the Voyager observations in 1979 [*McNutt et al.*, 1979], suggesting a change in this region of the Jovian magnetosphere between 1973 and 1979.

Surprising as this result is, a variety of considerations, which are explained in the discussion section, support its potential validity. We note here that if the M/Q ratio associated with this 1500- to 2000-V peak was as much as 32, the observed speed would still be approximately equal to the expected corotation speed and hence greater than the speed observed by Voyager.

In order to obtain a trend in the speed covering a longer time interval, spectra obtained earlier than those shown in Figure 1 were also examined. A large number of spectra had significant ion detections, and over a period of several hours (~1500 UT to ~2100 UT), a trend of decreasing speed with decreasing radial distance was evident.

Figure 3 is adapted from *McNutt et al.* [1979] and shows the nominal corotation speed (the dashed line), the component of nominal corotation speed into the Voyager detector (the solid line), the measured corotation speed from Voyager (the crosses below the line), and the measured corotation speed including standard deviations from Pioneer (the dots above the line). The values of the Pioneer speeds are estimates obtained by calculating the average speed corre-

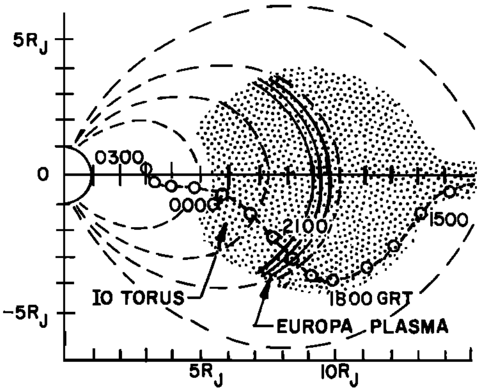

Fig. 4. Location of the region of detection of corotating ions in the vicinity of Europa on a portion of the 'wiggle diagram' indicating the Pioneer 10 inbound trajectory in Jovian magnetospheric coordinates. The Io plasma torus is also shown [*Intriligator and Miller*, 1981]. The latitude extent of the plasma shown is based on the motion of the spacecraft relative to the Jovian magnetosphere. The ions are assumed to extend along the field lines to the equator and are drawn symmetrically above the equator. The details of their spatial distribution cannot be uniquely determined from the single flyby.

sponding to the M/Q estimates in the spectrum where the principal peak is assumed to be $M/Q = 16$. For a given spectrum, the energy of the maximum current for each peak was determined and the speed for each peak was calculated. The average speed for the spectrum was then obtained.

The Pioneer speeds in Figure 3 indicate that the plasma speed during the Pioneer encounter is consistently higher than the expected corotation speed. This figure shows a downward trend in speed in the Pioneer data with decreasing radial distance that is as regular as the trend in the Voyager data. However, from Figure 3 it is evident that these magnetospheric plasma speeds during the Pioneer 10 encounter are systematically above the plasma speeds observed by Voyager in 1979 and above the expected nominal corotation speed (the dashed line in the figure).

Lane et al. [1981] have presented evidence based on the IUE observations that recycled sulphur ions may be present in the vicinity of Europa. In this case the ambient (Iogenic) sulphur ions are implanted on Europa and subsequently they are 'recycled,' giving rise to a local source of sulphur ions—S^+, SH^+, or H_2S^+, etc.—in the vicinity of Europa. Then the principal peak or shoulder in our spectra in Figure 1 would represent M/Q values of about 32. The radial profiles in Figure 2 would correspond to $M/Q = 32$ and 64, respectively, rather than $M/Q = 16$ and 32. In this event the Pioneer corotation speeds shown in Figure 3 would all be reduced ~30%, making them coincide more closely with the speeds expected for rigid corotation (the dashed line in Figure 3).

Figure 4 shows the trajectory of the spacecraft superimposed on the plasma regions inferred from the Pioneer 10 plasma data, as explained in more detail in the discussion section. The trajectory plot shows spacecraft locations in magnetospheric coordinates. We emphasize that the spacecraft was always at least 1.5 R_J south of the magnetic equator during the period associated with the data in Figure 3. The interval of enhanced plasma intensity near Europa's L shell was detected between 3 and 4 R_J south of the equator. Thus there is no possibility of mistaking the equatorial plasma sheet for a lunar enhancement.

DISCUSSION

This paper contains the first detailed analysis of the inbound Pioneer plasma observations in the vicinity of Europa. The data presented in the preceding section lead to a number of significant inferences concerning conditions in this region of the Jovian magnetosphere during the Pioneer 10 encounter in 1973 and concerning the possible relations of some of the inferred phenomena to the very different conditions during the Voyager encounters in 1979.

M/Q Ratio Determination

As indicated in the preceding section, a number of spectra show peaks at energies which appear to confirm our preferred identification of the mass to charge ratios in the range $M/Q = 16–18$. As already noted, several spectra in Figure 1 show distinct but lesser peaks at 1100 V, which is (to the accuracy of the measurements) 2/3 of the energy of the principal peak. We therefore associate this peak with an M/Q ratio of $10\frac{2}{3}$. This is the M/Q ratio for S^{3+} and there are several reasons for expecting this ion to be present in large quantities. S was detected by Voyager both remotely [*Broadfoot et al.*, 1979] and in situ [*Bagenal and Sullivan*, 1981] in 1979. The Pioneer 10 plasma analyzer detected large quantities of S^{++} in the Io torus [*Intriligator and Miller*, 1981). Sufficiently energetic particles are always present to ionize S^{++} ions further, particularly if the ions have a relatively long residence time in the magnetosphere.

Clear detections of a narrower peak at about 1/16 of the energy of the principal peak are much rarer, but two have been found between 1630 UT and 1700 UT. At these times the corotation speed is much higher than it is near Europa so that this peak is well above the low-energy threshold of the instrument. Its narrowness relative to the heavy ion peaks and its position at the low-energy end of the spectrum correspond with the numerous hydrogen peaks present in the published Voyager data (e.g., figures in the work of *Bagenal and Sullivan* [1981]). Both the Jovian atmosphere and the solar wind are possible sources for this hydrogen. Thus if this peak represents $M/Q = 1$, then our principal peak is $M/Q = 16–18$.

It is possible, but in our view less likely, that all of these identifications are erroneous. For example, if we are mistaken in our identification of corotating protons (peak $M/Q = 1$) and these ions are really corotating He^{++} ions ($M/Q = 2$), then our peak labelled $M/Q = 16$ would really be $M/Q = 32$, our peak labelled $M/Q = 32$ would really be $M/Q = 64$, and the peak labelled $M/Q = 10\frac{2}{3}$ might be $M/Q = 23$. However, Voyager detected H^+ ions, but few He^{++} ions; Voyager also detected a relatively large number of $M/Q = 32$ ions (S^+) but not many $M/Q = 64$ ions, and Voyager detected many $M/Q = 10\frac{2}{3}$ ions (S^{3+}) ions and not many $M/Q = 23$ ions (Na^+ ions). If our principal peak represented M/Q values of 48 or 64, the higher-energy detections would represent M/Q ratios of 96 or 128, and the low-energy peak would represent a mass of $M/Q = 3$ or 4. These identifications appear even less plausible and less consistent with other knowledge of the Jovian system.

In short, to obtain higher masses of our observed ions (and hence lower speeds), it is necessary to postulate a major difference between the chemical composition of the magnetosphere during the Pioneer and Voyager encounters. This difference would have to be so large that no plausible justification is readily apparent. In contrast, a mechanical explanation for different corotation speeds at different times is readily available as discussed in more detail below under the heading 'corotation and outflow.'

Like the Voyager experimenters, we find that our observations cannot consistently be explained by spacecraft charging alone. Since the Pioneer plasma analyzer observations indicate plasma energies above those expected for strict corotation, if there were spacecraft charging, the charge would have to be negative. The shift in energy of each ionic species from the expected value would be proportional to its charge. However, the spectra appear to show shifts proportional to the E/Q ratios of the ions as would be expected for a population of ions of different M/Q ratios all moving faster than expected.

It is possible that our interpretations of the data in Figures 1 through 3 are the result of a combination of charging and misidentifications of ion species. Possibly some combination of unexpected density ratios, more or less highly charged species, and spacecraft charges could be devised to explain each spectrum, but postulating a complicated series of composition and charge variations to explain them would require some explanation as to why the variations should follow so closely the expected behavior for the simpler explanation of mass addition from Europa and a persistently higher speed.

We do not wish to imply that there is no possibility of misidentifying individual peaks or that spacecraft charging was completely negligible at all times. In order to minimize time aliasing during this period the Pioneer plasma analyzer was not operating in the mode that provides the highest energy resolution. Some of the spectra show variations which could be the result of either modest spacecraft charging or the presence of unconsidered ion species.

As in the work of *Belcher et al.* [1980], our conclusion is model independent, because it is derived from a simple comparison of the energies of the spectral peaks with reliable assumed masses. The Pioneer 10 plasma analyzer employs quadrispherical deflection plates. This system measures the full energy of the incoming plasma and the solid angle integrated by each collector of detector B is less than 1/5 sr. The Pioneer results should be at least as reliable as the Voyager ones because even for transonic or subsonic plasma distributions sufficient accuracy for qualitative studies is available from the Pioneer plasma data without corrections for unknown components of particle motion, or the convolution of the spectrum with the instrument response over a large solid angle.

Ion Identification

These results show that during the 1973 Pioneer 10 encounter, significant changes in plasma properties were observed as the spacecraft approached and crossed Europa's L shell. We doubt that they were temporal fluctuations because it is improbable that temporal fluctuations would coincide so neatly with this approach and crossing of the L shell. A disturbance propagating inward from the spongy outer magnetosphere would be unlikely to so strongly affect the much denser inner magnetosphere where the plasma pressure is dominated by magnetic pressure and particles are very stably trapped.

The intensity variations in Figure 2 are consistent with the inferred chemical properties of Io and Europa, and present strong evidence for a plasma source at Europa. As discussed above, it is not possible to completely unambiguously identify these ions. In the subsequent discussion we will refer to the principal peak as $M/Q = 16$ and the secondary peak as $M/Q = 32$ but as indicated above these peaks instead may be associated with $M/Q = 32$ and 64 ions, respectively. If we examine Figure 2, we see an apparent background of ions at $M/Q \sim 16$ and 32, as expected for a gradual outflow from the Io torus. We also note that from 1945 UT to 2100 UT the intensity of ions at $M/Q \sim 10\frac{2}{3}$ also shows a gradual increase, but the time profile of this increase is different from those in Figure 2. The ions with $M/Q \sim 16$ and 32 show increased intensities between 1930 UT and 2030 UT, with detailed variations which are so similar (e.g., they are simultaneous, of comparable magnitude, and similarly shaped) that the most likely conclusion is that the added quantities of both types of ions come from the same source. Between 1930 UT and 2100 UT, $M/Q \sim 10\frac{2}{3}$, however, shows few changes and they do not match the changes in Figure 2. In particular, there is a continuous overall upward trend from 1945 UT to 2100 UT without the decrease at ~2030 UT shown in both panels of Figure 2.

These results are consistent with the identification of the added $M/Q = 16$ and 32 ions as being O^+ and O_2^+, respectively, from Europa. O^+ (and also OH^+ and perhaps H_2O^+) would be expected from the bombardment of the icy surface of Europa by the ambient energetic particle population. *Wu et al.* [1978] have discussed the chemistry of the formation of O_2 in an atmosphere around Europa. It follows that O_2^+ would also be expected from a source at Europa. Our observations thus could support the inference by Wu et al. that their UV observations represent detections of oxygen atoms. Their quantitative calculations, however, were done on the pre-Voyager assumption of a magnetospheric plasma dominated by light ions, without the benefit of the recently published Pioneer 10 plasma observations of the Io torus [*Intriligator and Miller*, 1981] and without the benefit of the laboratory experiments on keV heavy ion sputtering by P. K. Haff (preprint, 1981).

No ion formed from oxygen except a very improbable one, such as O_2^{3+}, can have $M/Q \sim 10\frac{2}{3}$. Thus we would not expect any enhancement from Europa of the ions in this M/Q range and we identify these ions as S^{3+} ions from Io. The absence of any intensity enhancement of the ions in this range in the Pioneer data is additional evidence that the enhancements in the other ions (as shown in Figure 2) are associated with oxygen added from a local source rather than local intensity variations of the Iogenic plasma.

The detections of ions at M/Q ratios of 32 and above could also represent recycled sulphur or sulphur compounds as implied by *Lane et al.* [1981] and the laboratory experiments of *Johnson et al.* [1981]. *Eviatar et al.* [1981] suggest that under these conditions sulphur could be a dominant ion. In this case one could identify the principal peak as $M/Q = 32$ as being S^+ ions (or SH^+ or H_2S^+ ions) and the next peak as $M/Q = 64$ as being SO_2^+ ions.

Evidence for a Source at Europa

The hypothesis of a Europa source may also explain some of the more detailed variations seen in the plots in Figure 2. The regularly spaced rises observable in both ion plots that we have attributed to added oxygen from Europa suggest some periodic process. The most basic periodicity in the

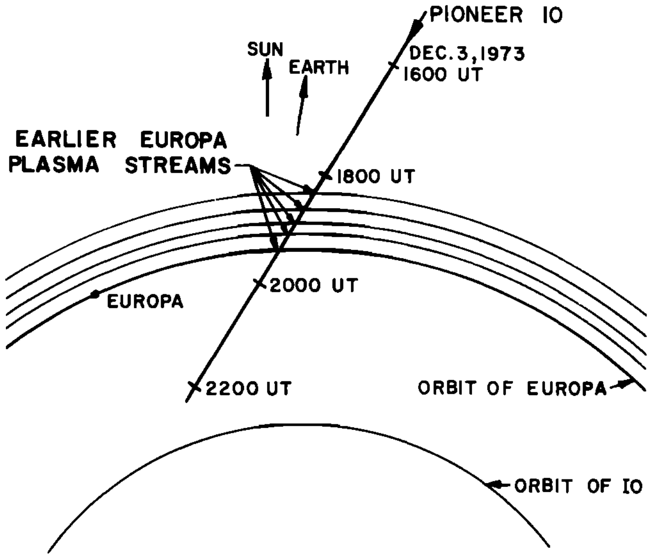

Fig. 5. Pioneer 10 crossings of Europa plasma streams (see text). The location of Europa is shown at the time Pioneer 10 crossed its orbit. This figure is drawn to scale.

Jovian magnetosphere is the 10-hour rotation. If the plasma in this region had little turbulence and a slow outflow speed, a regularly spaced spiral stream or layer of plasma from Europa would accumulate as depicted in Figure 5. Figure 5 is drawn to scale and therefore cannot show both the entire orbit of Europa and the spacing between the streams in a drawing of reasonable size. A large figure would show the plasma streams as forming a more or less tight spiral around Jupiter. Figure 5 depicts a portion of this structure. Then, as illustrated, along the Pioneer 10 trajectory there would be four (or possibly five) crossings of these Europa plasma streams. We suggest that this is precisely what we observe—successive layers of Europa plasma, respectively entrained about 54, 43, 32, 21, and 10 hours before their respective times of observation. We have taken into account the motion of Europa in its 84-hour orbit (Figure 5 indicates the location of Europa at the time that Pioneer 10 is crossing its orbit). We may also note the similarity of the inner edge of the ion profiles in Figure 2 to the precipice in the Io torus. At Europa the precipice is even steeper. This may be due to the outward force of the Io plasma.

The plasma streams from Europa would represent an obstacle to the outflow of Iogenic plasma. At the interface between the Europa and Io plasma, an increase in the density of the latter may occur as it decelerates and transfers outward momentum to the former.

Further insight may be obtained by considering the fluctuations in the apparently Iogenic S^{3+} and its possible scale height. The narrowness of the S^{3+} peaks in Figure 1 indicates that its temperature is low. Since these ions have a high mass, their scale height would be expected to be small. An examination of the data used for Figure 3 confirms that larger amounts of S^{3+} ions are detected between 1600 UT and 1700 UT than after 1700 UT, and that between 1800 UT and 1900 UT they are usually undetectable. This is consistent with a small-scale height and the latitude variations of the trajectory at these times (see Figure 4).

Several more inferences can be made when the compression of the magnetosphere by the solar wind is taken into account. The flows associated with the $M/Q = 16$ and 32 ion intensities plotted in Figure 2 clearly have a strong southward component. As shown in Figure 5, these observations were made close to local noon. This result confirms the observation by Voyager 1 [*McNutt et al.*, 1981] that significant compressive deflections were observed in magnetospheric plasma motion within 10 R_J of Jupiter as late in local time as 1400 LT (Voyager 2 reached periapsis at 10.1 R_J at 1800 LT and did not observe any compressive deflection there).

The flow would be generally along field lines, which slant toward Jupiter in this region as shown in Figure 4, and this would account for the inward component of motion [*Intriligator and Miller*, 1981] apparently needed to bring the plasma distribution into our instrument's field of view. Comparison with the Voyager results suggests that such compressive flows are likely to be a permanent feature of this region of the magnetosphere. We noted above that the external pressure on the magnetosphere may have been considerably higher than usual at the time the Pioneer measurements were made. The magnetic field this far inside the magnetosphere is presumably strong enough not to be greatly affected by such external pressure changes.

Magnetospheric compression by solar wind pressure appears to explain a subtle but significant aspect of the profiles of Europagenic oxygen ions in both panels of Figure 2. The plasma in the last enhancement between 2015 UT and 2030 UT was evidently emitted about 10 hours earlier, since Pioneer 10 is only 25° upstream of Europa. Given the 10 hours of outflow, invoked to explain the successive enhancement peaks in these profiles, the innermost enhancement should have been detected significantly outside the predicted position of the L shell if magnetospheric compression did not occur. The distance would be approximately the radial distance associated with the width of one of the enhancements. Evidently, the compression pushed the plasma back to the Europa L shell. It also appears that the compression can explain such a subtle feature in Figure 2 as the lesser separation between the last two enhancements in the profiles as compared with the separations associated with the earlier ones. Europa was near 1430 LT when Pioneer crossed its L shell. Ten hours earlier, when the plasma forming the last enhancement was being emitted, Europa was near 1130 LT, where compressive effects were already quite strong so that previously emitted plasma would have been somewhat pushed back toward Europa. When the plasma forming the earlier enhancements was emitted at 21, 32, 43, and 54 hours before the Pioneer 10 passage, Europa would have been at various locations of local night and early morning, where compressive effects are usually small or nonexistent. Thus it is reasonable that plasma streams emitted from these locations of Europa's orbit would be better separated.

We have discussed how a variety of aspects of the data in Figures 1 and 2 can be consistently interpreted in terms of a source at Europa, which provides plasma which acts as a 'tracer' elucidating the behavior of plasma in this region of the Jovian magnetosphere. We have emphasized the intensity variations displayed in Figure 2, because they show so many significant features which are not obvious from the original spectra in Figure 1. However, since the plots in Figure 2 are derived as summary data, it is necessary to check the original spectra to ascertain whether there is any reason to think that any misleading effects which are visible in the spectra could have occurred to cause us to misinterpret Figure 2. We want to rule out other possible explanations for the observed changes in the spectra in the vicinity of Europa and thereby to indicate that the most plausible explanation for the observations in the vicinity of Europa is a change in composition from a local source of emission.

The changes in the spectral shape in Figure 1 do not suggest a change in the speed of the plasma. A large, sudden speed change without changes of temperature or composition would shift the spectrum in energy without changing its relative shape much. This is not the case for these spectra which show such prominent peaks.

Possibly a more plausible alternative is an acceleration mechanism which either removes particles from the energy range observed by the instrument or alters the distribution in a manner which would mimic the changes we observe. In either case, it is necessary to explain why this mechanism would apparently only operate at Europa's L shell. To our knowledge, such a mechanism, with the necessary special characteristics, has not been theoretically predicted or inferred from experiment. The simplest explanation for the observed spectral change is a change in composition.

Several possible mechanisms could cause a composition change. If all the observed ions are derived from Io without any recycling through the surface of Europa, then some process operating in the plasma over a restricted range of radii at Europa's orbit changes the ion composition by recombining, further ionizing, accelerating, or trapping one species more than another. The operation of such a process would be unusually specific and localized and would have to produce a large variety of observed phenomena which are naturally expected from recycling through Europa's surface or mass addition by Europa. It seems at least as reasonable to consider whether these changes result from the addition to the plasma of ions derived from Europa's surface.

To our knowledge, Europa has not been suggested as a significant source of plasma for the Jovian magnetosphere since the initial reports of the Voyager encounter data, with their astonishing detection of the plasma of the Io torus. Nothing in the Voyager data has so far been interpreted as providing evidence for a plasma population associated with Europa. Io, the Jovian ionosphere, and the solar wind have been considered the three possible plasma sources, with the plasma largely concentrated into an equatorial sheet outside Io's orbit. Indeed, in a recent paper, *Eviatar et al.* [1981] conclude that Europa cannot be a significant plasma source in the magnetosphere. Their paper is based on the IUE measurements presented by *Lane et al.* [1981]. We are confident that our plasma data represent a direct observation of plasma from Europa. The resolution of this possible disagreement may be in considering the importance of large temporal variations. We will discuss the Voyager and IUE data below, after further consideration of the Pioneer data.

We must emphasize that in suggesting that Europa's surface is the source for ions which are added to the outward diffusing plasma at Europa's orbit, we are making no inferences about the mechanisms of material removal from Europa or of ionization. Ions could be released directly from the surface, or from an atmostphere by several processes, or neutral material could be released which is later ionized near Europa. As mentioned above, the experiments of P. K. Haff (preprint, 1981) and *Johnson et al.* [1981] are suggestive, but we cannot directly compare them with our data. Possibly some constraint is put on the range of possible mechanisms by the apparent evidence in our data that the plasma is emitted in a rather localized region, as indicated by the apparent persistence of separated streams after several Jovian rotations. We will compare this concept with available Voyager data below.

In Figure 4 we have indicated the location of the region of detection of corotating ions in the vicinity of Europa on a portion of the trajectory of the spacecraft in Jovian magnetospheric coordinates. In addition, we have shown the location of the regions of detection of corotating ions near Io [*Intriligator and Miller*, 1981].

The latitude extent of the regions depicted is based on the motion of the spacecraft relative to the Jovian magnetosphere. The ions are assumed to extend along field lines to the equator and are drawn symmetrically above the equator. Their actual presence at other latitudes cannot be determined uniquely from a single flyby. To date we have found no evidence of measurable corotating fluxes from Pioneer 11, whose trajectory is less favorable for ion detection. The radial extent of the torus outside of Europa is based primarily on the data used to determine the Pioneer speeds in Figure 3.

Corotation and Outflow

A number of more quantitative conclusions can be drawn from comparison of these results with Voyager data and other studies.

The lagging observed by the Voyager plasma experiment has been interpreted to be the result of mass loading: conservation of momentum causes plasma moving outward to lag behind corotation. The amount of lag depends among other things on the balance between the speed of outflow and the accelerating torque caused by the field-aligned (Birkeland) currents. The currents, in turn, depend on the ionospheric (Pedersen) conductivity, which, in turn, depends among other things on the temperature of the upper atmosphere, which is ohmically heated by those same currents. Thus there is a feedback effect possible which implies that the outflow speed of the plasma is not simply proportional to the density of the Io torus. During the Voyager encounter there was clearly a large degree of lag in the corotation speed (implying a rapid rate of mass flow out of the inner magnetosphere).

A large amount of theoretical and data analytic effort has been expended in order to understand the details of the Voyager observations. *Siscoe and Summers* [1981], for example, discuss the feedback system mentioned above, deriving and finding special solutions to the nonlinear equations describing diffusion under such circumstances. *Siscoe et al.* [1981] point out the added complications of energetic particle pressure. These reports and also *Richardson and Siscoe* [1981] assume that the outward motion is basically diffusive, while *Hill et al.* [1981] and others assume that the motions are organized into a large-scale convection system. The assumption of a convection system is generally linked to a magnetic anomaly model of the magnetosphere. *Vasyliunas and Dessler* [1981] summarize the arguments for this model and their reasons for viewing as premature the generally held judgment of the invalidity of this model. The outflow speed in a diffusion-dominated system might not show a dependence on Jovian longitude, perhaps depending on the importance of magnetic anomalies; but a convection-

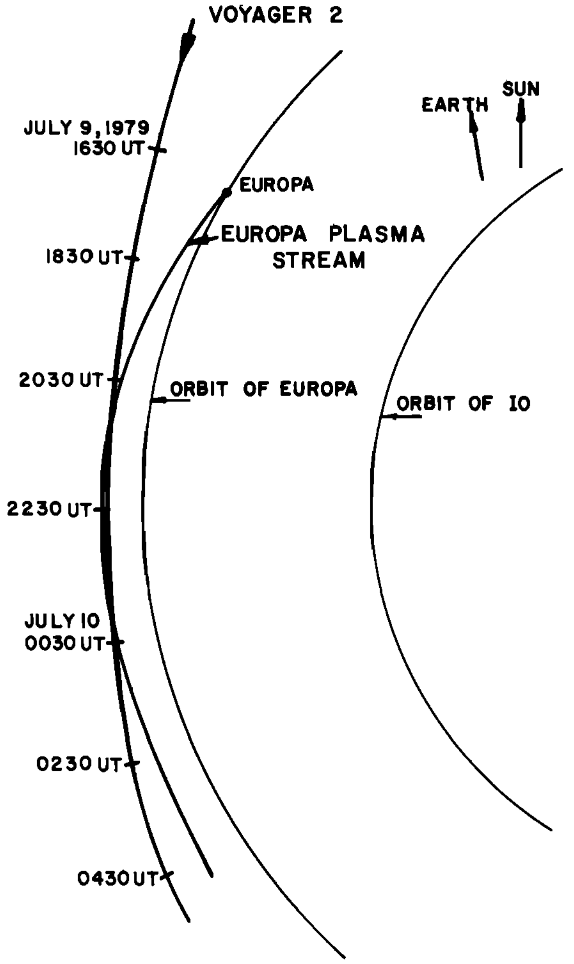

Fig. 6. Voyager 2 trajectory in the vicinity of Europa based on *Stone and Lane* [1979]. This figure is drawn to scale.

dominated system would, and the outflow speed might be locally higher than in a diffusion system.

Directly obtained estimates of outflow speed could be very useful in clarifying the outflow mechanism and also many problems of source strength which have implications for magnetospheric dynamics. Using the values of *Siscoe and Summers* [1981], we note that the strength of Io (2×10^{28} particles/s and average mass $m^* = 20$ amu, or 4×10^{29} amu/s) is less than the lower limit used by *Dessler* [1980]. The much higher values of 2.6×10^{30} amu/s and 5×10^{31} amu/s are used as lower and upper limits, respectively, in the calculations of *Hill et al.* [1981]. The Rice University group's convection calculations generally appear to assume larger source strengths and higher outflow rates than those employed by others.

The apparent accumulation of successive layers of Europa plasma provides a way to estimate the outflow speed during the hours preceding the Pioneer 10 traversal of the inner magnetosphere. Obviously an outflow rate cannot be estimated from a simple measurement of radial speeds. We have described inward motion of the plasma due to solar wind compression of the magnetosphere. However, if the spacecraft traverses one enhancement every 15 min and its radial component of velocity is approximately 0.75 R_J/h during this period (as shown in the wiggle diagram in Figure 4), then the spacing between the enhancements is 3/16 R_J. Since the plasma associated with the enhancements is emitted every 10 hours, this gives 3/160 R_J/h as the outflow speed, which is 1331 km/h or 0.37 km/s.

It is interesting to explore whether we can obtain a comparable estimate from the Voyager data. Figure 6 shows that Voyager 2 had a trajectory that was very favorable for detecting ions from Europa if any were present. Figure 7 is adapted from *McNutt et al.* [1981]. We have indicated with arrows below the data the peaks, which previously had been interpreted as magnetic equator crossings, that we consider to be plausible candidates to include detections of Europagenic plasma. This suggestion is strengthened by a careful examination of the plot which indicates that the edge closest to Jupiter (this is the final edge of the first peak and the initial edge of the second peak) of each peak is extremely abrupt. This is similar to the inner edge of our Europa enhancements in Figure 2. The edges of the undoubted equatorial sheet crossings elsewhere in this figure, and in the corresponding figure of McNutt et al., for Voyager 1 are not usually this sharp. We also note that in Figure 7 the first peak we associate with Europa is unusually narrow for an equatorial current sheet crossing and that it occurs more than an hour ahead of the calculated time indicated by the arrows above the data (to aid the reader in studying these two crossings we have included two arrows immediately above the data denoting the predicted magnetic equator crossing times).

Taking these two Voyager peaks as detections of Europa plasma, we can estimate the outflow speed. The inner edge of the first peak appears to be about 70 min before periapsis and the inner edge of the second appears to be about 80 min after periapsis. If the periapsis is at 10.1 R_J, and the motion of the spacecraft is 1 R_J/h over this restricted range, then the inbound and outbound inner edge detections are at approximately 10.17 and 10.19 R_J, respectively. They are separated by 14.1 degrees, or approximately 0.04 of a circle requiring 0.4 hour for corotating plasma to rotate through the angle. Thus the Voyager outflow speed is 0.02 R_J/0.4 h = 0.5 R_J/h

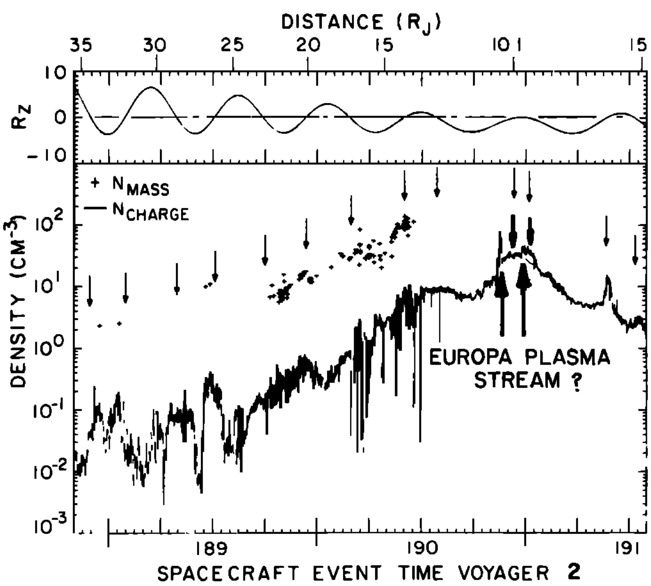

Fig. 7. Our identification of possible Voyager 2 detections of Europagenic plasma (denoted by arrows below the data). Magnetic equator crossings are denoted by arrows above data (adapted from *McNutt et al.* [1981]).

TABLE 1. Outflow Speed at $L = 9.5$

Basis for Estimate	Speed, km/s
Pioneer data	0.37
Voyager data (our estimate)	1
Diffusion theory [*Siscoe and Summers*, 1981]	0.2
Convection theory [*Hill et al.*, 1981]	17.6

= 3520 km/h or 1 km/s. This is roughly triple the Pioneer speed and like the change in corotation speed suggests that the mass loading was less during the Pioneer encounter.

Obviously this estimate for Voyager, being based on a published figure which may have accumulated inaccuracies, is more uncertain than the rate we calculated for Pioneer. Nevertheless, it is interesting that such a rough estimation method could yield a value which is not only of the same order of magnitude as the Pioneer value, but larger as expected for the slower corotation speed observed by Voyager. We hope that the Voyager experimenters will undertake a more accurate estimate to give a more quantitative understanding of the evident large change in magnetospheric mass loading.

Table 1 compares these experimental values with two theoretical ones. We obtained the Siscoe and Summers value by extrapolating their V_S $(L = 6) = 0.05$ value to $L = 9.5$ by their formula which makes $V_S \alpha L^3$ (i.e., $0.2 = 0.05\ (9.5/6)^3$). We also note that Figure 1 of Richardson and Siscoe shows that an L^3 dependence of N (and therefore V_R) fits the available Voyager PLS data quite well over the range 6–12 R_J and that the results of their nonlinear diffusion equation are extremely close to the L^3 dependence from 7 to 12 R_J. We obtained the Hill et al. estimate from their equation (26): $V_r \leq 2.8\ (9.5/6)^4 = 17.6$ for $L = 9.5$. Table 1 indicates that the observed speeds are bracketed by the theoretical rates. However, neither theory is disproved by these data because the Io source strength is unknown.

As the plasma density in the inner magnetosphere appears to have been much higher during the Voyager encounter than during the Pioneer encounter, it is likely that the densities of plasma emitted from Europa (and hence the source strength of Europa) were higher during the Voyager encounter than during the Pioneer encounter, although we do not presently have a quantitative estimate.

Now that we have discussed the evidence for Europa plasma detection in the Voyager data, we can make further comparisons with other reports. Our conclusion that the Voyager data show evidence for a significant density of plasma from Europa appears to be consistent with the conclusion of *Johnson et al.* [1981] that the erosion rate of Europa's surface may have been as much as 1000 Å per year at the time of the Voyager 2 encounter, but the apparent large temporal fluctuations inferred from comparing the Voyager and Pioneer data imply that all the data could be consistent with a much lower erosion rate as an average over several recent years.

This apparent variability is important to remember in considering the IUE observations of Lane et al. They observed UV absorption on the trailing hemisphere of Europa which they attribute to SO_2. They concluded that it was produced by deep implantation of impacting energetic sulphur ions. They conclude that equilibrium between implantation and plasma erosion of the surface required an erosion rate well below 1000 Å per year. Both the sputtering rate calculated by Lane et al. and the time constant for approaching equilibrium after a change, which may be inferred from their calculations, depend on the average depth of penetration into ice of the impacting sulphur ions. Little laboratory information is presently available on this subject as noted by Lane et al. *Eviatar et al.* [1981] present detailed arguments for a much shallower penetration and obtain a correspondingly smaller erosion rate and source strength. It is therefore interesting that Johnson et al. and P. K. Haff found that heavy ions were much more effective sputterers than light ions and that *Johnson et al.* [1981] report that 'the erosion rate [of water ice] was far greater than expected on the basis of contemporary [1978] sputtering theory.' It is precisely because such departures from theory have been recently observed that we need to be wary of extrapolation to estimate the behavior of 100-keV sulphur ions hitting Europa. Thus the available laboratory data and the IUE data are generally consistent with each other when Jovian magnetospheric variability is taken into account and both appear consistent with our analyses of the Voyager and Pioneer plasma detections.

One more quantitative determination can be made. Figure 3 shows that the speeds observed by Pioneer 10 typically agree with or range up to 30% above the nominally expected corotation speed for the radial distances shown. However, in the neighborhood of Europa's L shell, plasma observed by Pioneer 10 has travelled inward ~15% of its original radial position, so that momentum conservation implies a 15% excess in the tangential velocity component. The velocity, however, is directed about 30° south and somewhat inward of corotation. Thus the polar component must be more than one half the tangential component, representing work done on the plasma by the solar wind compression. The vector sum of these two components is then at least 15% above the tangential component or more than 30% above the expected corotation speed. This is in agreement with the upward range of our observed speeds and perhaps could be taken for arguing for the presence of oxygen ions. Thus it appears that the mass loading rate during the Pioneer encounter, as indicated by the low outflow speed, was low enough that motion close to the expected corotation speed was possible in the uncompressed part of the magnetosphere and that it is possible to account kinematically for the probable speed excess observed in the Pioneer data.

It is natural to ask if the outflow and inward compression motions discussed here can confirm or disprove the existence of large-scale convection such as described by *Hill et al.* [1981]. At this point an effort to resolve this question seems premature. The data from which we determined the Pioneer outflow speed estimate were gathered roughly equidistant between the 'active sector' and the 'inactive sector.' Our observations are probably too localized in longitude to give a useful determination in 1973 of whether large-scale convection was occurring. The approximate method by which we obtained the Voyager outflow speed estimate makes that result tantalizing but not definitive. We cannot predict whether the question of large-scale convection will be resolved in the future from data now available, but there is some satisfaction in being able to obtain results which seem consistent with more general considerations.

CONCLUSIONS

We claim that the Pioneer 10 plasma analyzer detected ions derived from Europa. The observations indicate that the ions are most likely O^+ ions, although OH^+ or H_2O^+ ions would also be consistent with the data. It is also possible that the ions are S^+ derived from recycled sulphur. In Figure 1 possibly the breadth of the peaks in the spectra from the densest part of the Europa region is due partly to the presence of these species which are closely spaced in M/Q, as well as to a relatively high temperature. For any of these ions or for a mixture of them, the species identification is consistent with emission and ionization of material from the icy surface of Europa.

These species identifications lead us to model-independent speed estimates greater than or equal to those expected for rigid corotation. The obvious alternatives to this interpretation of higher corotation speeds lead to contradictions with the data or to implausibilities much worse than unexpectedly high corotation speeds. Thus we have looked for a mechanism that might provide a possible explanation for this observation. It appears possible that the radial mass outflow speed through the middle magnetosphere can be much lower than it was during the Voyager encounter [*Hill et al.*, 1981].

We derive an estimated mean outflow speed of 0.37 km/s from our data and we derive 1 km/s from Voyager 2 data. These estimates are consistent with theoretical expectations if there was a major change in mass loading between 1973 and 1979. We also appear to be able to account kinematically for the greater corotation speed of the plasma in 1973 than in 1979 by momentum conservation and compression of the magnetosphere by the solar wind.

The assertion of plasma derivation from Europa is based on several lines of evidence. The profile of peak intensity for M/Q = 16 and 32 ions indicates an enhancement over the apparent background derived from Io. Moreover, this enhancement peaks close to the time predicted for crossing the Europa L shell. Laboratory experiments indicate significant emission of atoms or molecules by sputtering. The Voyager 2 data from the few hours around periapsis can be interpreted as showing that significant emission from Europa was occurring. However, the conditions for observing these emissions were much less favorable in 1979 than in 1973.

The topology of the Europa plasma torus probably changes depending on the speed of magnetospheric plasma outflow. At times it is a partial torus or a streamer (as we have shown for the Voyager data). At other times it may have a spiral configuration as illustrated by our Pioneer 10 analyses. Generally, the Europa plasma torus may not be as complete or durable as the Io plasma torus.

We remarked in our paper on the Io torus that the Pioneer plasma analyzer was surprisingly effective in obtaining information on the Jovian magnetosphere. In the present paper we have gone beyond confirming the Voyager results to obtain significant information on large-scale or long-term variations in the conditions in the middle Jovian magnetosphere between 1973 and 1979 and to take advantage of the more favorable conditions in 1973 for observing emission from Europa.

An obvious next step is to determine if plasma derived from Ganymede or Callisto was detected by the Pioneer 10 plasma analyzer, since the source strength of Io was apparently so much greater in 1979 than in 1973, thus tending to swamp faint plasma sources. The discussion above suggests that the Pioneer 10 data are more likely than the Voyager data to contain unambiguous evidence of such plasma.

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