Nature Vol. 280 30 August 1979

In situ identification of various ionic species in Jupiter's magnetosphere

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Positive ions with various mass per charge values up to ~160 have been identified within 20 jovian radii of Jupiter from the analysis of data from the plasma science experiment on Voyager 1.

ONE of the major surprises from the Voyager 1 encounter with Jupiter in March 1979 was the discovery[1] of active volcanoes on Io. This result emphasises the importance of Io as the principal source of the bulk plasma in the jovian magnetosphere[2,3]. The plasma science experiment[4] on Voyager 1 has made the first detailed *in situ* measurements of the plasma (10–5,950 V) near Jupiter[2]. Continuing analysis of these measurements for the ionic composition of this plasma has revealed the existence of further atomic and molecular ions as minor constituents of the plasma. We have now identified ions with mass per charge (A/Z^*) values of 1, 8, 10–2/3, 16, 23, 32, 64, ~104 and ~160 within 20 jovian radii, R_J, of Jupiter in the dayside magnetosphere.

The measurements used in the preliminary analysis reported here were taken in the high resolution mode (M mode) which has ~3.6% resolution in energy per charge between 10 and 5,950 V. The energy per charge scan effectively becomes a mass per charge scan whenever all ionic species have a common component of velocity into any sensor; this common component of velocity as well as the spacecraft potential are parameters of the present analysis. (The instrument contains four independent sensors[4] A, B, C and D, looking in different directions[5].) The measurements are usually displayed as relative distribution function versus energy per charge; the relative distribution function is the measured current divided by the energy per charge width of the particular measurement step. Since the step widths increase with increasing energy per charge, a constant background will result in a smaller value of the distribution function at higher values of energy per charge.

Significant heavy ion abundances are found beyond the inner magnetosphere where ions with $A/Z^* = 8$, 16, 32 and 64 were reported by Bridge *et al.*[2]. For example, at 19.6 R_J, the energy/charge spectrum (Fig. 1) shows several distinct peaks.

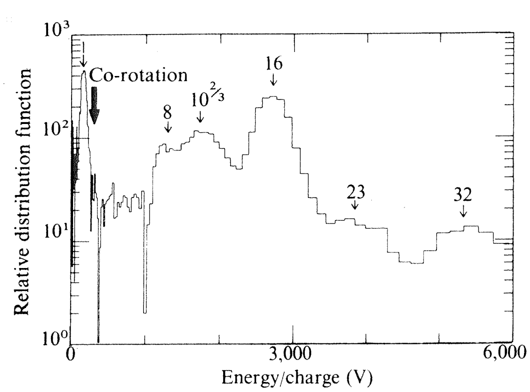

Fig. 1 D-sensor energy per charge spectrum obtained on day 63 at 15.50 UT when the spacecraft was at 19.6 R_J and a magnetic latitude of −8.5°. The heavy arrow labelled co-rotation marks the expected location of a proton peak moving with the geometrically expected co-rotation velocity. The light arrows mark the locations of various A/Z^* values assuming the lowest peak is a proton peak.

This spectrum is typical of the spectra for ~15 min about this time. Each spectrum is analysed with a simultaneous fit to a sum of convected isotropic maxwellian distribution functions with a common component of velocity; the sum is over peaks at $A/Z^* = 1$, 8, 10–2/3, 16, 23 and 32. The analysis of this spectrum gives a common component of velocity of ≃180 km s^{-1} and a spacecraft potential of less than ±5 V. The common component of velocity is not identical to the value of ≃240 km s^{-1} expected geometrically from co-rotation; this difference and related measurements are discussed by McNutt *et al.*[5]. The mass/charge values for the individual peaks obtained from the fit are within half a unit of the indicated numbers. Thus, we can make the following tentative assignments: $A/Z^* = 1$ is H^+; 8 is O^{2+} or S^{4+}; 10–2/3 is S^{3+} or even B^+; 16 is O^+ or S^{2+}; 23 is Na^+; and 32 is S^+ (or $O_2{}^+$?). The peak observed at ≃3.9 kV is most probably sodium and not magnesium or neon. This conclusion is based on the temperatures of the ions derived from the maxwellian fits; within ±20% all ionic species have the same temperature. Under these circumstances, it is possible to produce a peak at $A/Z^* = 23$ by an appropriate combination of Mg^+ and Ne^+. However, the temperature of the 'sodium' peak produced in this way is too high in comparison with temperatures of the other ions. There is a clear absence of a He^+ or He^{2+} peak; a rough upper limit can be put at $n\,(He^+, He^{2+}) < \frac{1}{15} n(H^+)$. Any signal from $A/Z^* = 64$ would come in at ≃10.8 kV well above our energy per charge scan range. The mass ratio of heavy ions to protons can be computed independently of the actual

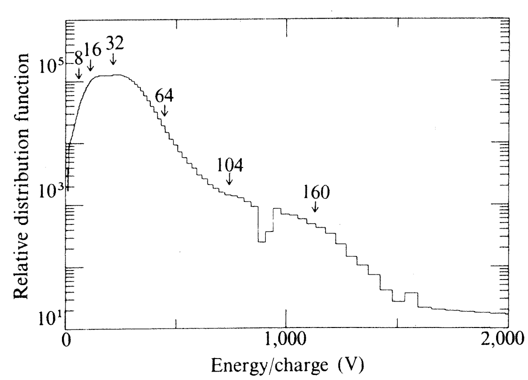

Fig. 2 C sensor energy per charge spectrum obtained on day 64 at 10.00 UT when the spacecraft was at 5.4 R_J and a magnetic latitude of +4.4°. The light arrows mark the locations of various A/Z^* values assuming strict co-rotation. The notch at ≃950 V is caused by interference from another experiment on the spacecraft.

mass and charge of the individual peaks as it depends on $(A/Z^*)^{3/2}$. The heavy ion to proton mass ratio is >95; consequently the mass density is dominated by heavy ions. It is instructive to compare these results with the inner magnetosphere results of ref. 2. First, the $A/Z^* = 23$ peak would have been masked by the prominent $A/Z^* = 32$ peak so that its absence at 5.3 R_J is not significant. Second, the relative abundances of 32 : 16 : 10-2/3 differ markedly; the higher ionisation states are enhanced at the earlier time, greater distance, reported here.

Direct measurement of values of $A/Z^* > 32$ were restricted to regions where the densities are high and the common component of velocity is small. Such is the case in the Io plasma

0028–0836/79/350798—01$01.00

torus where the instrument view directions were favourable for the A, B and C sensors[2,5]. Throughout this time protons moving with the geometric co-rotation velocity are below the energy/charge range of the instrument. Typical of the spectra in the torus is the energy/charge spectrum in Fig. 2; this spectrum is from the C sensor but the same results are obtained from the other two sensors (A and B). Compared with Fig. 1, the instrument gain has been reduced by a factor of ~77 in order to avoid saturation. Thus the detection threshold is raised and the curve above ≃1,600 V corresponds to the minimum detectable signal; consequently the graph only extends to 2 kV. The purpose of this figure is to establish the existence of detectable intensities of high mass/charge ions. The signal between ~500 and ~1,400 V shows a broad shoulder well above instrument threshold. We find acceptable fits to this spectrum including peaks at $A/Z^* = 104 \pm 5$ and 160 ± 10 moving with a common component of velocity equal to the co-rotation value; a clean peak at $A/Z^* = 64$ was shown in Fig. 5 of ref. 2, the spectrum at 10.15 UT. The spectrum at 10.15 UT also has a peak at 104 ± 5. These heavy ion peaks are almost certainly molecular ions. The $A/Z^* = 64$ peak could well be either SO_2^+ or S_2^+. The $A/Z^* = 104$ peak is not consistent within the error with ZnS^+ at 96. Speculative assignment for the $A/Z^* = 104 \pm 5$ and $A/Z^* = 160 \pm 10$ peaks may be made based on ions from sulphur salts or polymers which are suggested by observations of the surface of Io.

To conclude: inside 20 R_J: (1) The plasma is composed of ions with mass to charge ratios 1, 8, 10-2/3, 16, 23, 32, 64, ~104, ~160. (2) Wherever both protons and heavy ions are detected, the mass density is dominated by the heavy ions by a factor of ~100. (3) The plasma ions move with a common component of velocity which is not always the value expected geometrically from co-rotation.(4) The ions with $A/Z^* \geq 64$ are probably molecular ions.

We thank J. W. Belcher, H. S. Bridge, A. J. Lazarus and R. L. McNutt for helpful comments. This work was supported by NASA contract 953733.

Received 27 June; accepted 24 July 1979.

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Jupiter's magnetic tail

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Magnetic field observations of the jovian magnetosphere suggest an extended magnetic tail, which has been formed by solar wind interaction with the planetary field.

IN March 1979, Voyager 1 became the third spacecraft to penetrate and study *in situ* the magnetosphere of Jupiter. Earlier observations from Pioneers 10 and 11 in 1973–74 indicated the development of a magnetodisk topology describing the magnetosphere[1,2]. In this model, the combined effects of rapid rotation and a strong planetary magnetic field yield an equatorial region with a considerably enhanced charged particle and plasma population and distended magnetic field lines[3]. Thus, the central region of the magnetodisk effectively carries an azimuthal electrical current and this region is commonly referred to as the current sheet. Controversy arose over whether the current sheet of the magnetodisk was planar and parallel to the magnetic equatorial plane, with a spiraling of the magnetic meridian planes and field lines due to a finite Alfvén speed[4,5], or if the current sheet and magnetodisk were distorted due to the centrifugal forces and deviated or warped so as to become parallel to the jovigraphic equatorial plane at distances greater than 20 R_J (ref. 6). An attempt was also made to interpret the data qualitatively in the framework of a 'magnetic anomaly' model[7], based on the highly asymmetric planetary field[6,8], which did not include an azimuthal current sheet. All these earlier interpretations were based on a planet-centred view of the processes and mechanisms which control the configuration of the outer magnetosphere. We discuss here the Voyager I experimental observations which are most naturally interpreted in terms of a well developed magnetic tail on the nightside of the jovian magnetosphere. This tail, with a 'neutral sheet' separating the upper and lower lobes of opposite field polarity, is formed and controlled by the external forces associated with the solar wind interaction. The inner magnetosphere's current sheet is found to merge with the tail's neutral sheet. This configuration leads to a strong local time control of the outer jovian magnetosphere configuration, in contrast to earlier models which emphasised inner, that is planetary, control.

The preliminary results obtained from the Voyager 1 magnetometer have already been summarised[7]. The Voyager 1 spacecraft entered the jovian magnetosphere at 11.00 LT with magnetopause crossings observed at jovicentric distances between 67 and 47 R_J and left the magnetosphere at 04.00 LT with magnetopause crossings occurring between 153 and 170 R_J. Characteristic current sheet-neutral sheet signatures were observed in the magnetic field data, as the spacecraft passed through the magnetosphere. They showed up as significant decreases in the magnetic field intensity, occurring simultaneous with variations in the direction of the magnetic field. These are interpreted in the inner magnetosphere, $R < 30 R_J$, as evidence for a large scale azimuthal current or a current sheet within the magnetosphere.

Within 30 R_J, these magnetically characteristic regions occurred nearly simultaneous with the crossing of the magnetic equatorial plane. Although the field intensity decreased appreciably, it never reached zero, and the variation of field direction was gradual and not consistent with the nearly anti-parallel field directions on opposite sides of the current sheet which were observed at larger radial distances. Beyond 30 R_J, the characteristics of the current sheet crossings were similar to those seen when crossing the neutral sheet in the Earth's magnetic tail: a sharply defined dip in the field intensity, to very small values, while the field direction changed by approximately 180°. Within 80 R_J, there were two sheet crossings every 10 h, although not at a 5 h spacing. Beyond 80 R_J, complete traversals of the current sheet were not observed as evidenced in the field direction. However, very close approaches were made, as seen in the field intensity dips and increased higher frequency fluctuations which occurred with regularity at the 10 h rotation period of the planet. The times of the occurrence of the full traversals merged as the two traversals per rotation period changed to one partial traversal per rotation period.

0028-0836/79/350799—04$01.00