was close to Io's orbit, probably in the range 5.7 to 5.9 R_J; (ii) the maximum value of the electron density in the torus during the flyby was not less than 4500 cm^{-3}; (iii) the density gradient in the equatorial plane was larger inward than outward; and (iv) the bulge in the isodensity curve near 5 R_J was real.

In summary, the PRA experiment detected a plasma torus with high electron density in the magnetic equator at the distance of Io's orbit. The existence of this torus must be taken into account in theories of Jupiter's radio emissions.

Space scarcely allows more than a brief outline of further implications of our encounter data, from which we have introduced here only a small subset. High-frequency cutoffs apparent in decametric emission suggest occultation by the limb of Jupiter of emission from regions beyond the limb. Low-frequency cutoffs in hectometric emission when Voyager was within the plasma torus suggest external reflection of waves below the cutoff frequency. There is clear evidence for Faraday effect in decametric emission propagating through the torus. In a high data rate mode, used for a total of a few minutes each day throughout the encounter period, we have seen millisecond bursts in decametric emissions as well as very short bursts in the hectometric range. We have searched a limited set of these records for evidence of lightning, but the analysis is not yet conclusive. Finally, we have comparisons to make with Voyager 2, still bound for Jupiter and arriving there on 9 July 1979, with Earth-based stations observing Jupiter simultaneously with Voyager 1, and with the complementary experiments on both spacecraft.

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Low-Energy Charged Particle Environment at Jupiter: A First Look

Abstract. *The low-energy charged particle instrument on Voyager was designed to measure the hot plasma (electron and ion energies ⩾ 15 and ⩾ 30 kiloelectron volts, respectively) component of the Jovian magnetosphere. Protons, heavier ions, and electrons at these energies were detected nearly a third of an astronomical unit before encounter with the planet. The hot plasma near the magnetosphere boundary is predominantly composed of protons, oxygen, and sulfur in comparable proportions and a nonthermal power-law tail; its temperature is about 3×10^8 K, density about 5×10^{-3} per cubic centimeter, and energy density comparable to that of the magnetic field. The plasma appears to be corotating throughout the magnetosphere; no hot plasma outflow, as suggested by planetary wind theories, is observed. The main constituents of the energetic particle population (⩾ 200 kiloelectron volts per nucleon) are protons, helium, oxygen, sulfur, and some sodium observed throughout the outer magnetosphere; it is probable that the sulfur, sodium, and possibly oxygen originate at Io. Fluxes in the outbound trajectory appear to be enhanced from ~ 90° to ~ 130° longitude (System III). Consistent low-energy particle flux periodicities were not observed on the inbound trajectory; both 5- and 10-hour periodicities were observed on the outbound trajectory. Partial absorption of > 10 million electron volts electrons is observed in the vicinity of the Io flux tube.*

We report preliminary results from measurements obtained with the low-energy charged particle (LECP) instrument on board the Voyager 1 spacecraft during its traversal of the Jovian magnetosphere. The primary objectives of the LECP investigation were to make measurements at low energies (⩾ 15 keV and ⩾ 30 keV for electrons and ions, respectively), to characterize the composition of the particle population, to determine the particle anisotropies, and to search for particle effects associated with Io and its flux tube. The instrument consists of two basic sensors, the low-energy particle telescope (LEPT) and the low-energy magnetospheric particle analyzer (LEMPA), designed to provide measurements in the outer and inner magnetosphere, respectively. The LEPT is primarily a composition instrument capable of identifying the major ion species, while LEMPA performs basic ion-electron measurements at low and high energies with good particle separation over a large (~ 1 to 10^{11} cm^{-2} sec^{-1} sr^{-1}) dynamic range. The overall sensor complement contains 23 solid-state detectors ranging in area from 1.3 mm^2 to 13.8 cm^2 and in thickness from 2.3 μm to 2.4 mm, combined in various configurations. An essential feature is a stepping motor which rotates the sensors in eight steps through 360° in time intervals of either 48 or 192 seconds. A full description of LECP has been given elsewhere (*1*).

Overview. The first indication of the proximity of the Jovian magnetosphere was obtained on 22 January at ~ 600 Jupiter radii, R_J, when sunward-moving ions (> 30 keV) were observed for a brief (about 2 hour) period. The frequency and duration of such occurrences increased as the spacecraft approached Jupiter, culminating in a sustained increase at 180 R_J lasting for approximately 1 day (days 53 to 54) during which sulfur ions were also observed. The anisotropies, composition, and spectra indicate a Jovian origin for these particles.

Figure 1a shows the intensity profiles of selected ion and electron channels during the inbound traversal of the magnetosphere, which began on day 59 with the first bow shock crossing at ~ 85.6 R_J. There were at least five bow shock and magnetopause crossings between 85 and ~ 47 R_J, each of which has obvious signatures in both the electron and ion intensities (Fig. 1a). The diffuse nature of the bow shock boundaries is evident in the energetic ions, particularly for the

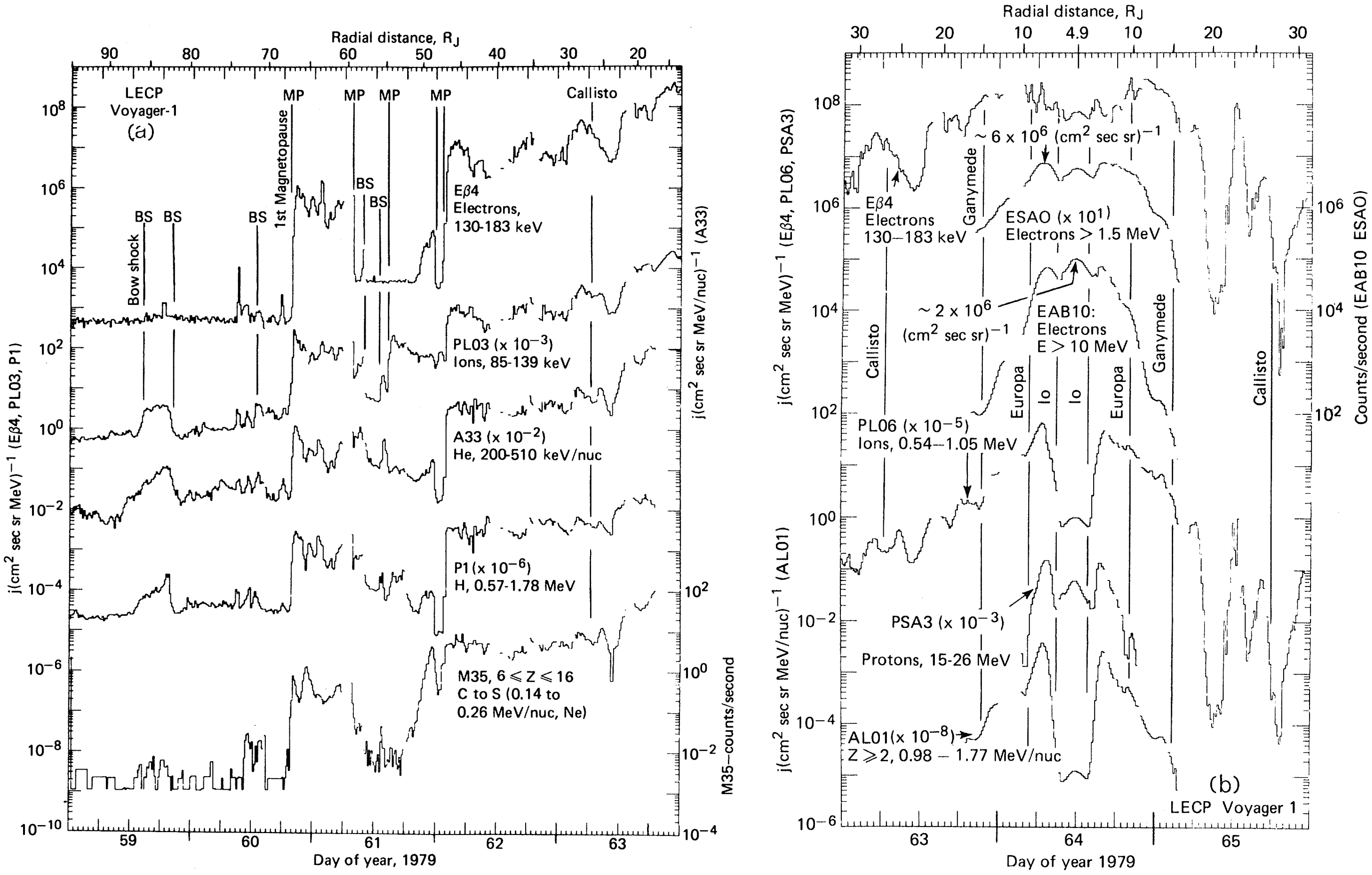


Fig. 1. (a) Measurements of LECP flux (15-minute averages) on the inbound pass to Jupiter. (b) Measurements of LECP flux (15-minute averages) in the inner Jovian magnetosphere.

heavier species (for example, helium on day 59). A large peak in heavy ions (primarily oxygen and sulfur) is observed just prior to the last two magnetopause boundary crossings late on day 61, with no equivalent counterpart in the hydrogen or helium profiles. Additional features shown in Fig. 1a include several intensity peaks, some of which are separated by 5 or 10 hours. However, in contrast to some reports from the Pioneer 10 encounter (*2, 3*), a sustained periodicity of either 5 to 10 hours is not observed. We note that the measurements shown in Fig. 1a are at lower energies than those generally obtained by Pioneer 10.

Data obtained during the 3 days surrounding closest approach are shown in Fig. 1b; late on day 63 the LEPT sensors were turned off and high-energy, high-intensity detectors in LEMPA were activated. The Eβ4 curve is continued from Fig. 1a, and peaks in intensity at ~ 4 × 10^8 electrons (cm² sec sr MeV)$^{-1}$ outside the orbit of Io. High-energy electrons are counted in channels ESA0 (singles rate) and EAB10 (coincidence rate), with peak fluxes as indicated; both intensities are comparable to those measured by Pioneer 10 (*4*). The most notable feature of the measurements is the effect of Io on particles of various energies. Electrons in the million electron volt energy range are clearly depleted at the Io L-shell, but increase again inside it; the amount of increase is largest for the highest energy (> 10 MeV) electrons. Lower energy (~ 130 keV) electrons appear to be generally enhanced around the L-shell, in agreement with Pioneer 10 observations (*5*). The effects of absorption are more dramatic for low-energy (≥ 0.6 MeV) ions and energetic (15 MeV) protons; the decreases range up to a factor of ~ 400. Preliminary analysis of lower energy (~ 30 keV) data suggests that the intensity of these ions tends to increase

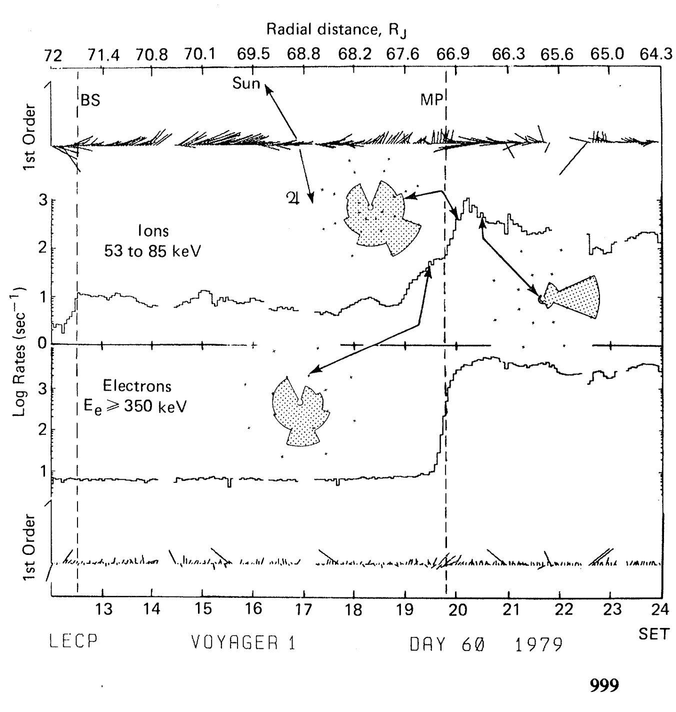


Fig. 2. Particle intensities and flows around the interval of the first magnetopause crossing.

Table 1. Abundances of energetic particles relative to oxygen.

Element	Jupiter's magnetosphere (0.6 to 1.6 MeV per nucleon)* Day 60, 1956 to day 61, 0754† (67 to 59 R_J)	Day 61, 2226 to day 62, 0227 (49 to 47 R_J)‡	Day 62, 0230 to day 62, 1230 (47 to 40 R_J)	Earth's magnetosphere (17) (0.4 to 1.5 MeV per nucleon)*	Solar flare particle events (18) (1 to 20 MeV per nucleon)*	Solar corona (19)	Solar system (20)
H	1480	6.4	230	~ 8700§	4600	1780¶	1480
He	7.4	0.33	3.3	~ 125	70	100	103
C	0.13	<0.02	~ 0.22	2.7 ± 0.4	0.54	1.0	0.55
O	≡1	≡1	≡1	≡1	≡1	≡1	≡1
Na	0.02 to 0.07‖	0.03 to 0.09‖	0.03 to 0.11‖	—	0.016	0.005	0.0028
S	0.35	0.35	0.34	<0.02	0.026	0.0251	0.023
Fe	<0.02	<0.009	<0.02		0.15	0.093	0.039

*Approximate energy range of measurements. †Spacecraft event time. ‡May include both magnetospheric and magnetosheath periods. §The proton value is an average, not included in (17). ¶Derived from solar wind He/O ratio (21). ‖Range from assumption of either equal amounts of Ne, Na, and Mg or all Na.

much more quickly inside Io and to exhibit a peak at periapsis. Data examined at the pre-Io peak (0630 to 0655) suggest that the He/O ratio at ⩾ 0.3 MeV per nucleon ranges from about 6 to 16, while the H/He ratio is about 3 to 16. Both ratios are spectrum-dependent and the provisional numbers quoted here should become better defined with detailed analysis.

The effects of the other Galilean satellites are rather small. They are most noticeable in the case of Europa in the low energy ions. Effects at Ganymede are also evident; the situation is more difficult to assess for Callisto. We note that after about 0700 spacecraft event time (SET) on day 65, a modulation has begun in the intensities, with minima about 10 hours apart and relative minima approximately every 5 hours.

Bow shock and magnetopause crossing. Spin-averaged (192 seconds) ion and electron counting rates and first-order particle anisotropies are shown in Fig. 2 for the interval around the first magnetopause crossing (~ 67 R_J). The ion rates are enhanced immediately behind the bow shock (identified from the low-energy electron fluxes in Fig. 1a). The electron and ion rates are enhanced in front of the magnetopause (also identified from the low energy electron fluxes). Inspection of high time resolution data indicates that the magnetopause is not sharply defined on a time scale of several minutes.

Immediately prior to the magnetopause crossing the ion and electron flows were away from the planet. Upon crossing the magnetopause the flows changed to the corotational direction. Details of the particle counts in each sector at three selected time intervals during the magnetopause crossing are shown as insets to Fig. 2. Prior to the magnetopause crossing the flow was directed away from Jupiter; during the crossing the flow began to change toward the corotational direction; after the crossing the flow was strongly corotational. It should be noted that this is not an azimuthal anisotropy caused by the proximity of the magnetopause (6), because it persists for several hours after the initial crossing.

The convected particle flux anisotropies and the particle energy spectra are used to deduce the Jovian hot plasma characteristics shortly after the first magnetopause crossing. The angular distribution of 30- to 54-keV ions in sectors 2, 3, and 4 (inset to Fig. 3a) can be fitted if one assumes that only protons are being convected (7) at the corotation speed ~ 800 km/sec; however, the ion counting rates in sectors 5, 6, and 7 are far in excess of what is expected from protons alone.

Proton spectra from LEPT in sector 4 are plotted in Fig. 3a. With the ions in LEMPA sector 4 also being assumed to be protons there is good spectral agreement over five orders of magnitude between the two detector systems. By us-

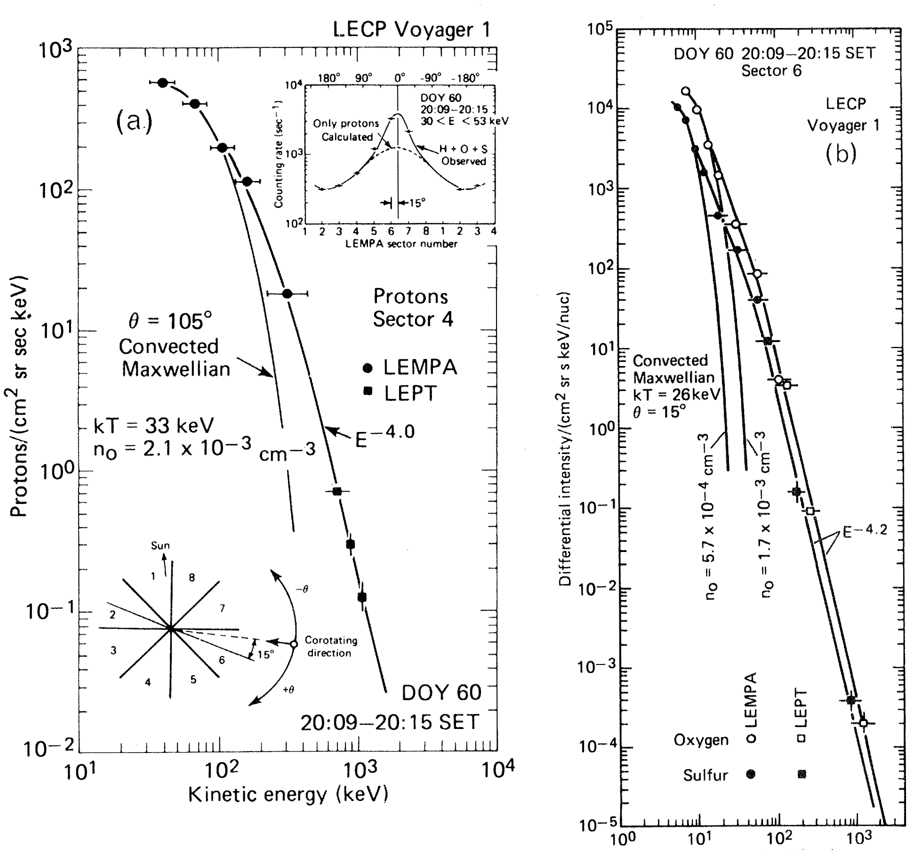


Fig. 3. (a) Proton spectrum in the outer magnetosphere together with a convected Maxwellian distribution fit

$$j(\epsilon, \theta) = C\epsilon \exp\left\{-\frac{\epsilon M}{kT}\left[1 - 2\left(\frac{\epsilon_c}{\epsilon}\right)^{1/2}\cos\theta + \frac{\epsilon_c}{\epsilon}\right]\right\}$$

where j is intensity, M is the particle mass number, ϵ_c is $1/2\ V_c^2$, and V_c is the corotating velocity. (b) Oxygen and sulfur spectra in the outer magnetosphere, together with a convected Maxwellian distribution fit.

ing this proton spectrum the contribution of protons to the ion rate in sector 6 (corotating direction) can be determined; it is shown by the dashed line in the inset of Fig. 3a.

At energies $\geq$ 100 keV per nucleon the abundance ratio for O/S was about 3 (Fig. 3b). If we assume this ratio holds (for equal particle velocities) at lower energies and that the "excess" ions in sector 6 are O and S, the spectra of O and S over an intensity range of $\sim 10^8$ can be deduced, as shown in Fig. 3b. The agreement between the LEPT composition determinations and the LEMPA composition assumptions at $\sim$ 100 keV per nucleon gives confidence in the procedure.

The extended curves in Fig. 3, a and b, are convected Maxwellian distributions characterized by a temperature T and particle number density n_0. Both T and n_0 are adjusted to fit the intensities at the lowest three energy intervals for all three ion species. All three ion spectra can be characterized by a "thermal" Maxwellian distribution and a nonthermal tail represented by a power law in energy. The proton and oxygen number densities are similar; the total n_0 is $\sim 5 \times 10^{-3}$ cm^{-3}; this value compares favorably with the density measured by the plasma wave instrument (*8*). The temperature of all three ion species is similar, $\sim$ 3 to 4 $\times$ 10^8 K. The energy density of the corotating ions near the magnetopause is $\sim$ 190 eV/cm^3, essentially equal to the magnetic field energy density. The deviation from the "thermal" to the nonthermal component occurs at $\sim$ 1.5 to 2.5 times the characteristic speed $(2\ kT/m)^{1/2}$; the nonthermal spectral index for all components is similar (Fig. 3, a and b).

Composition. Figure 3b shows that Jovian magnetosphere composition at the first magnetopause crossing is most unusual. Figure 4 shows an element abundance histogram (elements $Z \geq 6$) for the interval just outside and into the final magnetopause crossing (Fig. 1a; 2226 day 61 to 0227 day 62 SET). Superimposed as a dotted line is a solar flare particle histogram measured by LEPT in September 1977. Relative to the flare, we note the overabundance of O and S relative to C and Fe in the outer magnetosphere. There is also a small but significant peak at Na, and we can establish an upper limit for K at $\sim$ 20 percent of S.

Summarized in Table 1 are the measured Jovian ion ($\sim$ 0.6 to 1.6 MeV per nucleon) abundances (referenced to O) at three radial distances in the inbound portion of the trajectory. Element abundances of other solar system plasma sources are given for comparison, together with the commonly accepted solar system abundances. In view of optical observations of S and Na (*9*), it is probable that the source of these ions, and possibly of O, is at Io.

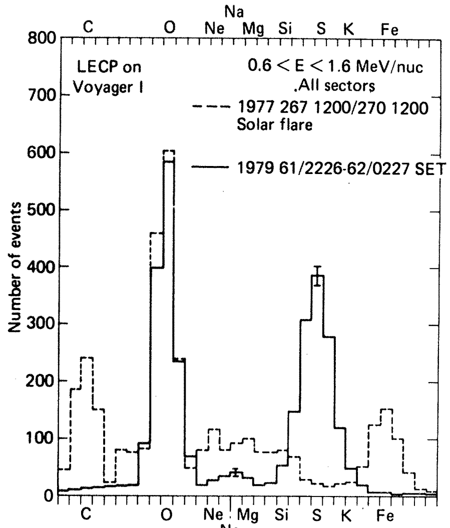


Fig. 4. Relative Jovian and solar flare particle compositions.

Io flux tube. A prime mission objective—passage through or in close proximity to the Io flux tube—occurred during about 1500 to 1511 SET on day 64. The enhancement in low energy electron fluxes may be related to a similar electron enhancement reported from Pioneer 10 (*5*); the extended enhancement seen by LEMPA may be because the Voyager trajectory was close to the Io orbit for nearly an hour before and after flux tube passage.

The scan-averaged high energy electron (> 10 MeV), proton (15 to 26 MeV), and low energy ion (0.28 to 5.2 MeV per nucleon) fluxes at the time of closest Io flux tube passage are shown in Fig. 5. An inset shows the pitch angles measured by the illustrated particle channels. The particle gyroradii are shown. A decrease of about 30 percent is seen in the highest energy electrons. The ions, with only slightly larger gyroradii, show only a small decrease (channel Pδ9) or ledge (channel Pδ′9) in the fluxes. The highest energy protons are not affected. Examination of the LEMPA data shows no pronounced enhancements of particle fluxes at the pitch angles sampled at the time of closest encounter with Io. Examination of the > 10 MeV electron fluxes in eight pitch angle bins between about 30° and 120° shows some angle selectivity in the particle "absorption" during closest approach; the selectivity is complicated and appears time variable in the interval $\sim$ 1500 to $\sim$ 1515 SET; the pitch angle distributions require further detailed study.

The absence of total particle absorption by Io [as is seen for Earth's moon, for example (*10*)] and the pitch angle "selectivity" of the absorption indicate that some particle deflection by Io was occurring, whether or not the actual flux tube was intersected. Mechanisms for the particle deflection include distortion in the ambient field produced by a conducting ionosphere, the conductivity of the satellite itself, or even an intrinsic Io magnetic field. It should be possible to

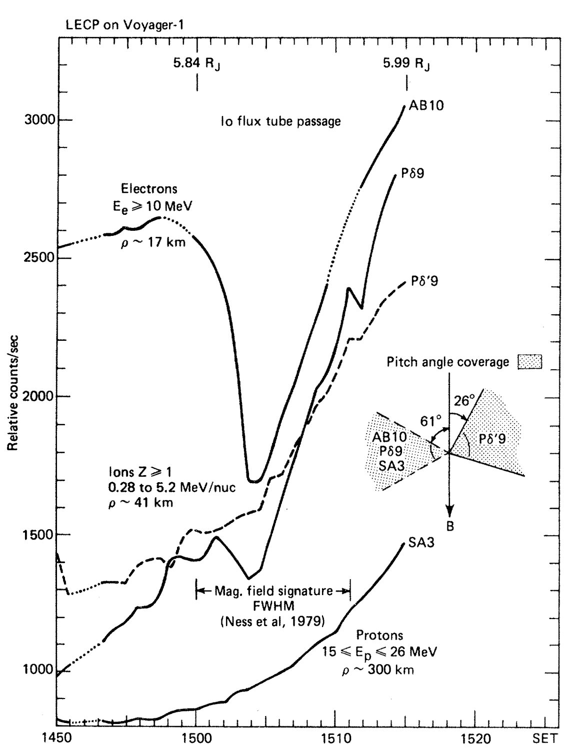


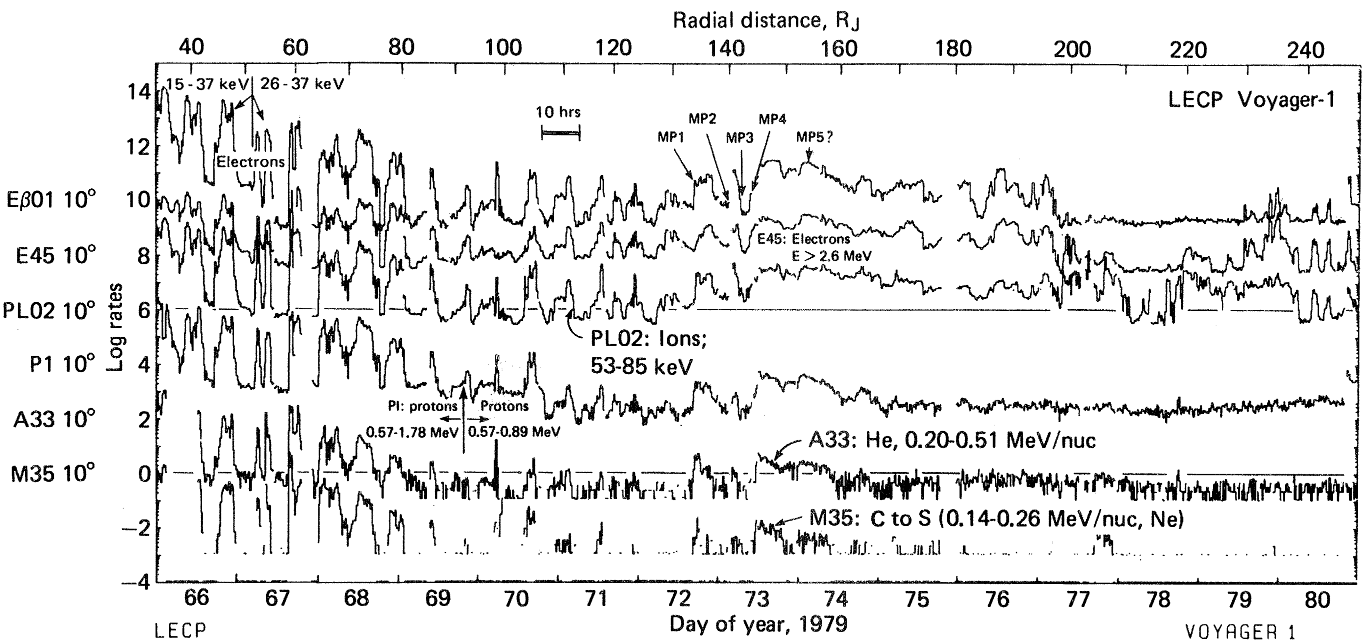
Fig. 5. Particle intensities in the vicinity of the Io flux tube. The interval of magnetic field signature of the flux tube is shown (*11*).

determine the nature of this deflection and compute the strength of a hypothetical Io magnetic field from the detailed study of the pitch angle distributions. No large ion or electron flux increases were observed at pitch angles $\geq 20°$. This is consistent with only strongly field-aligned particle flow toward or away from Io or a "miss" of the actual flux tube (*11*).

Outbound. Measurements of several particle species during the outbound pass are shown in Fig. 6 for days 66 through 80. There is a double peak in the intensity profile for days 66 through 68, with relative minima separated by 5 hours; this pattern appears to break down on day 69; then on day 70 a similar but less distinct pattern forms and persists through the first apparent magnetopause crossing on day 72. The most pronounced periodicity is clearly at 10 hours and lasts through the first magnetopause crossing. A suggestion of a continued 10-hour periodicity exists for days 73 through 76, especially for the 2.6-MeV electrons. It appears that multiple bow shock crossings occurred on days 76 and 77, with a number of downstream particle bursts observed through day 80. There appears to be a qualitative change in the decay of peak intensities after 85 R_J, with successive intensity maxima reaching a constant level. The heavy-ion channel (M35) showed only sporadic activity after that distance, with the exception of increases on days 73 and 74. A cursory examination of composition data during the outbound pass suggests large enhancements of O and S, similar to the inbound pass composition. Detailed composition studies have not been completed.

Particle flow directions in the instrument scan plane (inclined about the sun-spacecraft axis at $\sim 68°$) for days 66 through 72 were consistently sunward, with the exception of energetic electrons which appeared isotropic. An example of such flows is shown in Fig. 7, including three intervals of magnetic field reversals (*11*). No discernible changes in the anisotropy occur during reversals; the overall intensity profile is very broadly peaked around such regions. This behavior is characteristic of other field reversal intervals from days 66 through 69.

Discussion. The data presented in this report have important implications on proposed models of the Jovian magneto-



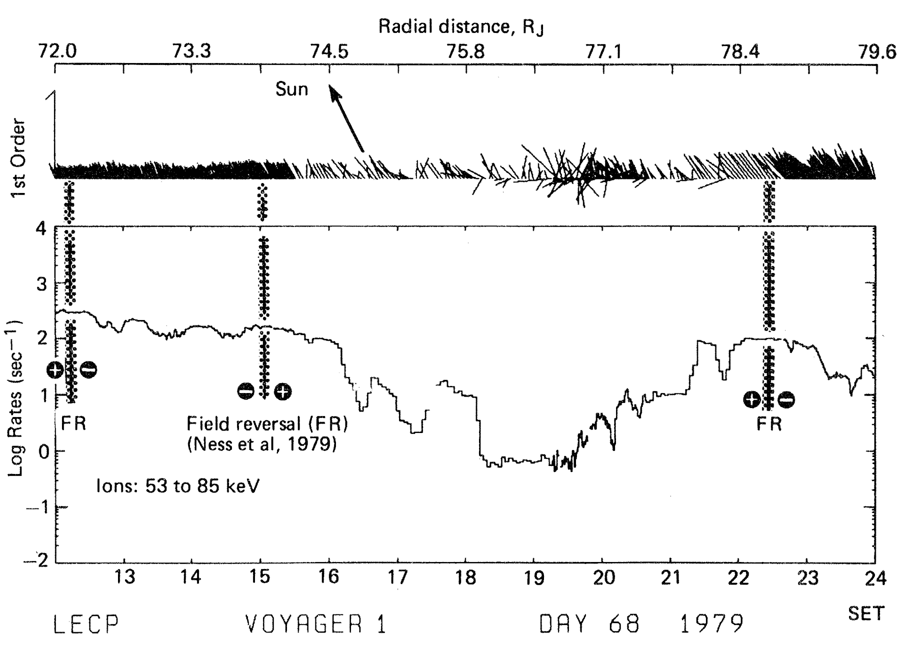


Fig. 6 (above). Measurements obtained with the LECP on the outbound pass through the Jovian magnetosphere. The suggested magnetopause crossings were assigned on the basis of reversal of the ion flow from sunward to tailward. Fig. 7 (left). Particle intensities and flows in an interval with three magnetic field reversals. The LECP scan period changed several times between 48 and 192 seconds.

sphere [reviewed in (*12-14*)]. During the outbound pass the 5-hour periodicity suggests on the one hand that a rigidly rotating magnetodisk (*2*) is probably a viable model to a distance of ~ 85 R_J, and perhaps to ~ 130 R_J. On the other hand, the data could be consistent with a "warped" disk beyond ~ 85 R_J (*15*). Since neutral sheet crossings were not seen after day 69 (*11*), one would expect that the difference in longitude between the dipole axis and the observed intensity peaks would be about 180°. We find the intensity peaks tend to occur at about 90° to 130° longitude (System III), while the dipole axis is located at about 200° longitude, a difference of 90°. This seems to be at variance with the magnetodisk model. A 10-hour periodicity is predicted by the magnetic anomaly model (*13*). The relation between the particle enhancements at about 90° longitude and the magnetic anomaly at about 230° longitude is not known. Finally, no evidence was found in the magnetosphere inside the magnetopause for radial outflow of hot plasma on either the inbound or outbound passes, indicating that a "planetary wind" or "breeze" (*16*) was not operating at Jupiter during the Voyager 1 passage. Flow directions in Fig. 7 are consistent with convective flow (*12*) which could be a combination of corotational and field-aligned components resulting in an overall sunward vector.

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24 April 1979

Voyager 1: Energetic Ions and Electrons in the Jovian Magnetosphere

Abstract. *The observations of the cosmic-ray subsystem have added significantly to our knowledge of Jupiter's magnetosphere. The most surprising result is the existence of energetic sulfur, sodium, and oxygen nuclei with energies above 7 megaelectron volts per nucleon which were found inside of Io's orbit. Also, significant fluxes of similarly energetic ions reflecting solar cosmic-ray composition were observed throughout the magnetosphere beyond 11 times the radius of Jupiter. It was also found that energetic protons are enhanced by 30 to 70 percent in the active hemisphere. Finally, the first observations were made of the magnetospheric tail in the dawn direction out to 160 Jupiter radii.*

The observations of the cosmic-ray subsystem (CRS) experiment during the Jovian flyby of Voyager 1 have added significantly to our knowledge of Jupiter's giant and dynamic magnetosphere and its complex relationship to the solar wind and the Jovian moons. Here we present data on the spatial and temporal intensity variations of electrons and protons, the flow patterns of the protons, and the ion composition from lithium through iron. These data confirm and extend much of the morphology reported by the Pioneer 10 and 11 investigators of a chaotic outer region dominated by azimuthal asymmetries and temporal variations with an equatorial current sheet, large field-aligned streaming of the energetic protons, and the occasional presence of a planetary wind in the more distant regions (*1-3*). Inside 20 Jupiter radii (R_J) a classical magnetosphere prevails with durable trapping but with the added complexity of the sweeping effects of the Jovian moons. The CRS experiment measures the three-dimensional flow pattern of the energetic ions as well as their detailed composition. Furthermore, the near-equatorial trajectory allowed measurements on both sides of the current-sheet region.

The instrument consists of seven multielement particle telescopes that are designed primarily to study the charge and energy spectra of low and medium energy galactic cosmic rays (*4*). During portions of the encounter, many systems were saturated by the high counting rates. Those data have either been corrected or eliminated from this discussion.

Energetic particle morphology. A small solar proton event, with no associated increase in nuclei with charge $Z \geq 6$, was in progress prior to the first bow shock encounter at 85.6 R_J, and the primary flow direction of energetic protons (0.4 to 8 MeV) was toward Jupiter.

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