The model sketched in Fig. 9a for the Jovian equatorial plane magnetosphere resembles in its plasma flow patterns the Jovian magnetosphere model discussed a decade ago by Brice and Ioannidis (*12*); that model, however, did not include either the wind or the hot plasma. We have not discussed the mechanisms for generating a convection electric field, particularly if magnetic merging at the plasmapause is not important, nor the effects of such a field. The shapes of possible Jovian current sheets have been discussed previously (*4, 15, 18, 19*). In view of our results, acceleration mechanisms proposed to date that are predominantly "single-particle" (*20*) are not capable of raising the bulk temperature of the magnetospheric plasma to the values we have measured.

S. M. Krimigis
Applied Physics Laboratory, Johns Hopkins University, Laurel, Maryland 20810
T. P. Armstrong
Department of Physics and Astronomy, University of Kansas, Lawrence 66044
W. I. Axford
Max-Planck Institute for Aeronomy, D-3411 Katlenburg-Lindau 3, West Germany
C. O. Bostrom
Applied Physics Laboratory, Johns Hopkins Univessity
C. Y. Fan
Department of Physics, University of Arizona, Tucson 85721
G. Gloeckler
Department of Physics and Astronomy, University of Maryland, College Park 20742
L. J. Lanzerotti
Bell Telephone Laboratories, Murray Hill, New Jersey 07974
E. P. Keath, R. D. Zwickl
J. F. Carbary
Applied Physics Laboratory, Johns Hopkins University,
D. C. Hamilton
Department of Physics and Astronomy, University of Maryland

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17. We note that at the interface where magnetospheric plasma is moving in the corotation direction and solar wind plasma in the tailward direction, one should expect excitation of large plasma instabilities and possibly a boundary layer. Evidence for such effects is seen at ~ 0800 to 1200 hours on day 203, where a tailward plasma beam exhibits a sharply peaked spectrum with maximum intensity at an energy of ~ 150 keV. In addition, large dawn-to-dusk asymmetries over the entire magnetosphere should be expected.
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Voyager 2: Energetic Ions and Electrons in the Jovian Magnetosphere

Abstract. *The Voyager 2 encounter has enhanced our understanding of earlier results and provided measurements beyond 160 Jupiter radii* (R_J) *in the magnetotail. Significant fluxes of energetic sulfur and oxygen nuclei (4 to 15 million electron volts per nucleon) of Jovian origin were observed inside 25* R_J, *and the gradient in phase space density at 12* R_J *indicates that the ions are diffusing inward. A substantially longer time delay versus distance was found for proton flux maxima in the active hemisphere in the magnetotail at Jovicentric longitudes* $\lambda_{III} = 260°$ *to 320° than in the inactive hemisphere at* $\lambda_{III} = 85°$ *to 110°. These delays can be related to the radial motion of plasma expanding into the magnetotail, and differences in the expansion speeds between the active and inactive hemispheres can produce rarefaction regions in trapped particles. It is suggested that the 10-hour modulation of interplanetary Jovian electrons may be associated with the arrival at the dawn magnetopause of a rarefaction region each planetary rotation.*

The passage of Voyager 2 through the Jovian magnetosphere demonstrated that this magnetosphere is highly variable, even as close as 10 Jupiter radii (R_J) from the planet. The cosmic-ray subsystem (CRS) measured the flux, elemental composition, and anisotropy of energetic particles. Its high sensitivity was particularly valuable during the long passage through the magnetotail, where particle fluxes were orders of magnitude less than in the inner magnetosphere and approached interplanetary values. The new data confirm earlier observations (*1–4*) that the Jovian magnetosphere is a giant accelerator of particles—electrons, protons, and heavy ions, including sulfur. We observed both spatial and temporal changes in the magnetosphere as compared to prior observations with Pioneer 10 and 11 (*2, 3, 5*) and Voyager 1 (*1*).

Energetic particle morphology. After final entry into the subsolar hemisphere at 61.5 R_J (*6*), proton and electron fluxes observed during the inbound pass (Fig. 1) were in general consistent with earlier observations (*1–3*). One difference with Voyager 1 observations, both inbound and outbound, however, was the smooth change with distance of proton intensity maxima inside 35 R_J. These maxima occur at magnetic equatorial crossings which fall alternately at Jovicentric longitudes $\lambda_{III} \sim 100°$ and $\sim 300°$ (Fig. 1). In the case of Voyager 1, crossings in the active hemisphere ($\lambda_{III} \sim 300°$) (*7*) were substantially more intense (*1*) than in the inactive hemisphere ($\lambda_{III} \sim 100°$).

As shown in Fig. 2, the proton flux ($E > 2.5$ MeV) was unusually variable between 17 and 13 R_J on the inbound pass, a period which falls within ± 4 hours of the closest approach of Voyager 2 to Ganymede. It is not clear whether this effect corresponds to a general magnetospheric disturbance or is due to Ganymede's interaction with the ambient medium.

Voyager 2 went farther into the magnetotail than earlier missions (*2, 8*). Between 20 and 60 R_J the spacecraft remained within ± 3° of the Jovigraphic equator. Thus the magnetic equator passed over the instruments approximately every 5 hours and produced a regular intensity modulation of protons and electrons (Fig. 1). The modulation of protons ($E > 2.5$ MeV) between 20 and 23 R_J, however, was only a factor of 10 at midnight as observed on Voyager 2 in comparison with a factor of 200 observed near dawn during the outbound pass of Voyager 1 at the corresponding distance and latitude. Comparable differences were observed for electrons and protons at other energies. Therefore, relatively close to the planet, the particle trapping region near midnight extends over a greater latitude range than in the dawn region (*1, 2*).

It is possible that the latitudinal extent of the energetic particle trapping region is controlled by the pressure balance between the Jovian magnetic field, trapped thermal plasma, and solar wind pressure. When a section of the magnetosphere rotates from the subsolar hemisphere into the antisolar direction, the trapped thermal plasma can expand radially outward because the solar wind pressure is removed. However, the expansion speed is limited by the Alfven velocity, which falls in the range of 15 to 60 R_J/hour (300 to 1000 km/sec) for reasonable densities and field strengths (*3*). Therefore, the latitudinal extent of the trapped energetic particle distribution is greater near midnight, where the expansion of the magnetosphere has progressed less far into the magnetotail, than at dawn. The thinnest trapping region should occur just before the expanded region rotates into the dawn magnetopause.

Figure 3 shows the time differences between crossings of the model magnetic equatorial plane (*9*) and the occurrence of proton flux maxima, which are generally closely associated with crossings of the actual magnetic equatorial plane (*6*). This time delay is a measure of the outward speed of propagation of the magnetic disturbance produced by Jupiter's rotating tilted magnetic dipole (*10*). In the range from 20 to 80 R_J, crossings in the active hemisphere at longitudes λ_{III} = 260° to 320° appear to be more regular and occur with a greater time delay than crossings in the inactive hemisphere

Table 1. Elemental abundances (relative to oxygen ≡ 1) of energetic heavy nuclei at different radial distances from Jupiter.

Element	Energy (MeV nucleon^{-1})	Relative abundances*			
		25 to 70 R_J†	10.6 to 25 R_J†	10.1 to 10.6 R_J†	4.9 to 5.8 R_J‡
C	6.2 to 10.5	$0.38^{+0.20}_{-0.14}$	0.29 ± 0.05	0.07 ± 0.03	
C	7.8 to 10.5		0.48 ± 0.13	≲ 0.13	
C	7 to 14				≲ 0.03
N	6.2 to 10.5	$0.13^{+0.13}_{-0.07}$	0.06 ± 0.02	$0.02^{+0.02}_{-0.01}$	
N	7 to 14				≲ 0.07
O		1	1	1	1
Na	7 to 14				0.04 *C* 0.02
S	7.8 to 10.5	≲ 0.18	0.18 ± 0.07	$0.62^{+0.24}_{-0.19}$	
S	7 to 14				0.76 ± 0.09

*Upper limits (≲) are at the 84 percent confidence level. †Voyager 2. ‡Voyager 1.

Table 2. Phase space densities of oxygen ions at magnetic equator crossings. Magnetic field values are from (*16*).

Radius (R_J)	Energy (MeV nucleon^{-1})	Magnetic moment (MeV nucleon^{-1} G^{-1})	$J_\perp(\geq M)$ (cm^2 sec sr)$^{-1}$	$[J_\perp(\geq M)]/B$ (cm^2 sec sr G)$^{-1}$
10.1 to 10.4*	≥ 7.8	2400	50†	0.14†
11.7 to 12.5‡	≥ 4.2	2400	240†	1.4†
12.5 to 13.5§	≥ 4.2	3100 (2400)‖	100†	0.8 (1.8)†‖

*Average of two magnetic equator crossings at day of the year (DOY) 190, 2120 to 2321, and DOY 190, 2331 to DOY 191, 0130. †The uncertainties are less than a factor of 2. ‡DOY 190 at 1245 to 1446. §DOY 191 at 0816 to 1014. ‖When extrapolated down to M = 2400 MeV nucleon^{-1} G^{-1}, $J_\perp/B$ = 1.8.

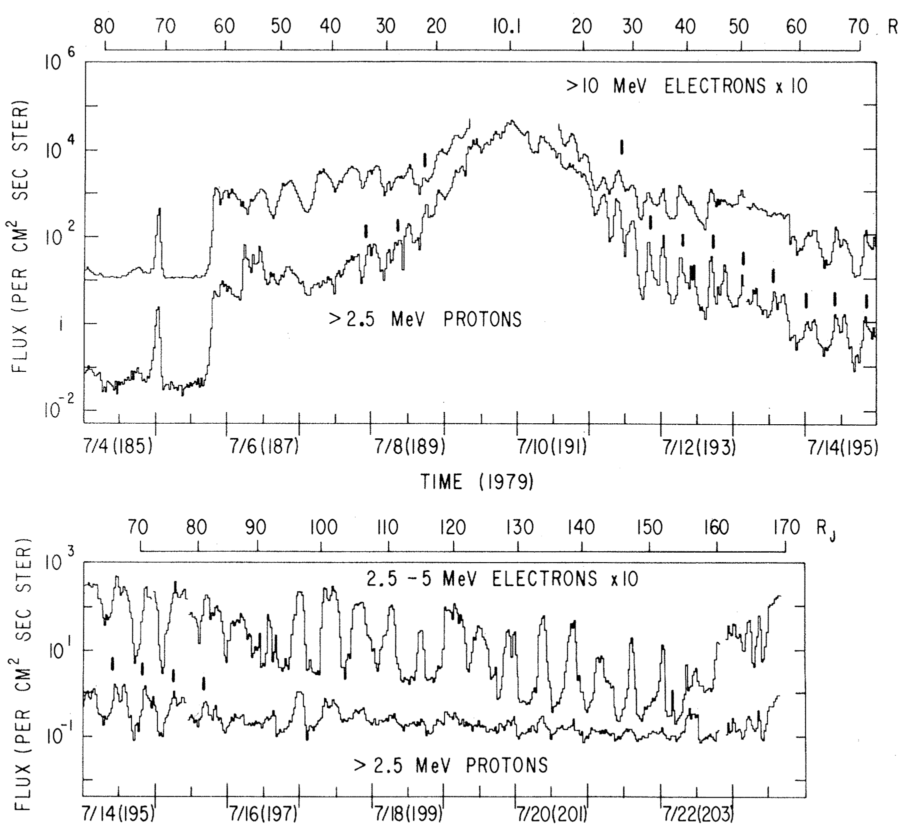


Fig. 1. Electron and proton fluxes (32-minute averages) observed during the Voyager 2 encounter. Electron fluxes are 1/10 of the left scale. Proton flux maxima corresponding to magnetic equatorial crossings in the active hemisphere have been identified with tick marks.

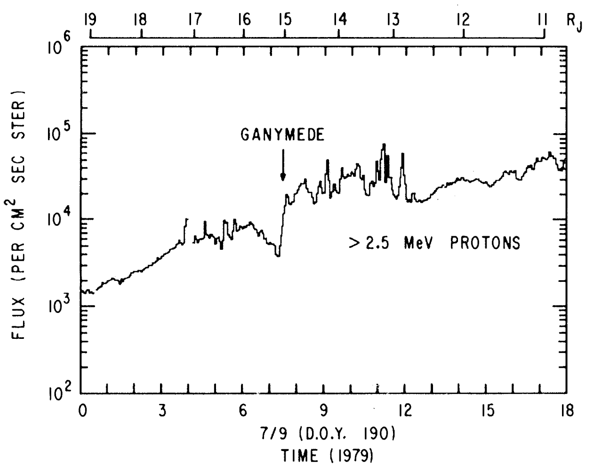


Fig. 2. Approximate intensity of protons with energies above 2.5 MeV (3.2-minute averages) observed during the inbound pass between 19 and 11 R_J. Note the large intensity fluctuations at 15 ± 2 R_J, which fall within ± 4 hours of the closest approach to Ganymede.

at λ_{III} = 85° to 110°. Data between 22 and 82 R_J give radial velocities of 22 and 42 R_J/hour for the active and inactive hemispheres, respectively.

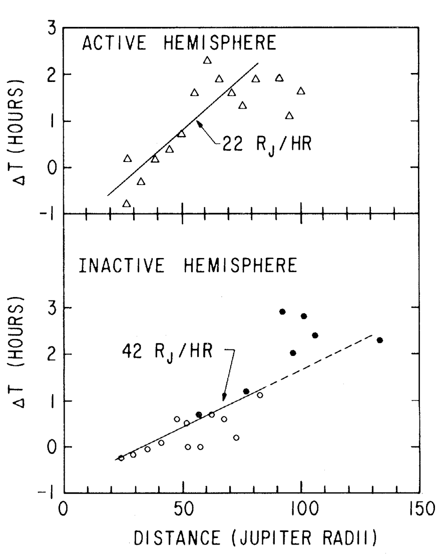
Since the expansion speed is slower in the active hemisphere, a rarefaction region will develop ahead of the plasma expanding from the active hemisphere. This region would be characterized by a low flux of > 6-MeV electrons because of the near absence of field lines with feet at lower magnetic latitudes. If the interplanetary Jovian electrons are preferentially released when the edge of the expanded plasma disk rotates into the dawn magnetopause at about 90 R_J, then a flux minimum and the softest electron spectrum would be observed when the rarefaction region reaches the magnetopause. This should occur about 2 to 3 hours after the feet of the field lines at the leading edge of the active hemisphere have rotated past the dawn meridian. When the rarefaction reaches the dawn magnetopause, the subsolar longitude is $\lambda_{III} \sim 240°$, consistent with the phase of the 10-hour modulation of Jovian electrons in interplanetary space and in some regions of the outer Jovian magnetosphere (*11*). The soft spectrum and sharp minimum in the flux of > 6-MeV electrons is the most characteristic feature of this modulation. A flux maximum would be expected when the transition from the active to the inactive hemisphere reaches the dawn magnetopause.

Between 100 and 150 R_J, the proton flux maxima (> 2.5 MeV) become weak and poorly defined even though plasma sheet crossings are observed (*6*). Energetic electron fluxes in this region show a 10-hour modulation. From 150 to 170 R_J, the periodic intensity modulation disappears (Fig. 1). A preliminary analysis of the first-order anisotropy of > 2.5-MeV protons at flux maxima indicates that the anisotropy beyond 150 R_J differs by about 180° from that observed inside 100 R_J, with maximum flux now coming approximately from the dawn direction. During this period, either conditions in the tail must have been very disturbed or the well-organized Jovian equatorial plasma sheet does not extend this far.

Energetic ions. The energetic particle composition ($7 \leq E \leq 14$ MeV per nucleon) observed with the Voyager 1 CRS (*1*) was reported for an inner region ($\leq 5.8\,R_J$) and an outer region ($\geq 11\,R_J$). Anomalous abundances of oxygen, sodium, and sulfur were observed in the inner region, whereas in the outer region the composition was solar-like. From the preliminary analysis, the relationship between the anomalous fluxes inside 5.8 R_J and the lower energy oxygen and sulfur nuclei in the outer magnetosphere (*4*) was not clear.

In order to link the observations in the outer and inner magnetosphere, the Voyager 2 CRS was configured to maximize the data return for the anomalous fluxes. The observed abundances are summarized in Table 1 for three regions (25 to 70 R_J, 10.6 to 25 R_J, and 10.1 to 10.6 R_J) and are shown for the inner two regions in Fig. 4. For comparison, Voyager 1 results (4.9 to 5.8 R_J) are also given in Table 1. There is a systematic enhancement of oxygen and sulfur with respect to carbon and nitrogen with decreasing radial distance; this enhancement is also observed at lower energies (*12*). Thus, the Voyager 2 data evidently illustrate the gradual evolution of the high-energy nucleon composition from the solar-like character observed earlier in the outer magnetosphere to the anomalous composition in the inner magnetosphere.

In order to determine whether the anomalous species are diffusing inward or outward, a gradient in the phase space density of the oxygen nuclei has been derived from the Voyager 2 data. During radial diffusion, conservation of the magnetic moment of a particle mirroring near the magnetic equator results in a particle energy E proportional to B, the local magnetic field intensity (*13*). In the absence of losses, the flux $J_\perp$ of particles with constant magnetic moment M varies directly with B; that is, the phase space density $J_\perp/B$ is constant, and loss mechanisms such as pitch angle scattering will result in a gradient in $J_\perp/B$. The gradient will be larger for larger loss rates and smaller diffusion coefficients. Each time the spacecraft crosses the



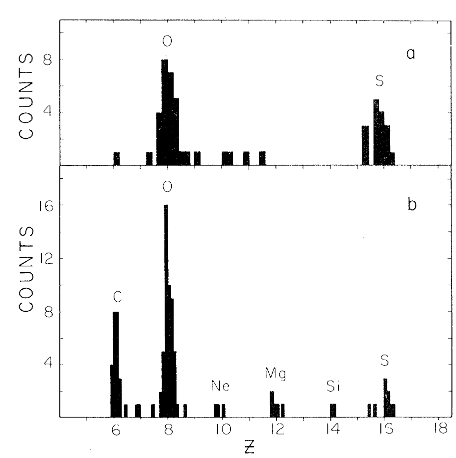


Fig. 3 (left). Time differences (Δ*T*) between crossings of the model magnetic dipole equator and occurrences of proton flux maxima. Crossings between λ_{III} = 260° and 320° are shown as △, crossings for λ_{III} = 85° to 110° as ○, and crossings attributed to maximum dipole tilt away from the spacecraft (λ_{III} = 21°) as ●. Where multiple crossings were observed (with a 16-minute time resolution), all points are shown. Multiple crossings occurred primarily in the inactive hemisphere. The straight lines constitute a fit to points between 22 and 82 R_J. Proton flux maxima observed in the inactive hemisphere [see also (*1*)] beyond 80 R_J appear to be associated with maximum dipole tilt away from the spacecraft. Fig. 4 (right). Measured element (*Z*) distribution in the energy range from 7.8 to 10.5 MeV per nucleon for heavy nuclei in the Jovian environment: (a) 10.1 to 10.6 R_J; (b) 10.6 to 25 R_J.

magnetic equator, $J_{\perp}$ can be determined with the low-energy telescope which is oriented nearly perpendicular to the magnetic field.

The results in Table 2 show that the phase space density $J_{\perp}/B$ at constant M decreases by a factor of ~ 10 between 12 and 10 R_J. The positive radial gradient in $J_{\perp}/B$ is a direct indication that the anomalous oxygen (and probably the sodium and sulfur as well) is diffusing inward. In the mid-magnetosphere ($B \sim 10^{-4}$ G), these particles would have energies $E \gtrsim 240$ keV per nucleon. Substantial intensities of oxygen and sulfur ions at these energies were detected by both Voyager 1 and Voyager 2 in the outer and middle magnetosphere, but with lower intensities during the Voyager 2 encounter (*4*, *12*).

The spectra of the oxygen ions with energies between 4.2 and 14 MeV per nucleon between 10 and 25 R_J can be well represented by $dJ/dE \sim E^{-\gamma}$, with $\gamma = 4.5 \pm 0.5$. The value of the spectral index γ changes little in the region from 10 to 25 R_J and is similar to that observed near 220 keV per nucleon in the outer magnetosphere on Voyager 1 (*4*). A radial diffusion process would preserve such a power law spectrum, provided that the loss processes were energy-independent.

The source of anomalous oxygen and sulfur in the outer magnetosphere or in the solar wind may be similar to that proposed by Eviatar *et al.* (*14*), who suggested that charge exchange between corotating sodium ions and neutral atoms in the Io sodium cloud could result in fast neutral sodium atoms which escape from Io's orbit and populate the outer magnetosphere and solar wind. The reionization of the sodium atoms was proposed as the source of sodium ions, which would then be subsequently accelerated through inward radial diffusion. Such high-energy sodium nuclei were observed by Voyager 1 (see Table 1). The Voyager 2 results suggest a similar source for low-energy oxygen and sulfur ions in the outer regions based on the reionization of fast neutral oxygen and sulfur atoms which may have been produced from the corotating oxygen, sulfur, and sulfur dioxide ions in the Io torus (*15*).

R. E. VOGT
A. C. CUMMINGS
T. L. GARRARD
N. GEHRELS, E. C. STONE
California Institute of Technology, Pasadena 91125
J. H. TRAINOR, A. W. SCHARDT
T. F. CONLON, F. B. MCDONALD
NASA Goddard Space Flight Center, Greenbelt, Maryland 20771

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Plasma Wave Observations Near Jupiter: Initial Results from Voyager 2

Abstract. *This report provides an initial survey of results from the plasma wave instrument on the Voyager 2 spacecraft, which flew by Jupiter on 9 July 1979. Measurements made during the approach to the planet show that low-frequency radio emissions from Jupiter have a strong latitudinal dependence, with a sharply defined shadow zone near the equatorial plane. At the magnetopause a new type of broadband electric field turbulence was detected, and strong electrostatic emissions near the upper hybrid resonance frequency were discovered near the low-frequency cutoff of the continuum radiation. Strong whistler-mode turbulence was again detected in the inner magnetosphere, although in this case extending out to substantially larger radial distances than for Voyager 1. In the predawn tail region, continuum radiation was observed extending down to extremely low frequencies, ~ 30 hertz, an indication that the spacecraft was entering a region of very low density, ~ 1.0×10^{-5} per cubic centimeter, possibly similar to the lobes of Earth's magnetotail.*

The Voyager 2 flyby of Jupiter, which occurred in July 1979, provided the second opportunity to study plasma waves in the vicinity of Jupiter (the first measurements were made by Voyager 1, which flew by Jupiter in March 1979). Because of the somewhat different trajectory and plasma conditions at Jupiter, the Voyager 2 mission provided new perspectives for analyzing many of the phenomena detected by Voyager 1 and also revealed the presence of several new types of plasma waves. For a survey of the Voyager 1 plasma wave observations at Jupiter, see Scarf *et al.* (*1*). Starting about 6 months before the closest approach of Voyager 2, intense radio emissions from Jupiter were detected by the Voyager 2 plasma wave instrument at kilometric wavelengths. Closer to the magnetosphere, sporadic bursts of electron plasma oscillations and ion acoustic waves were observed upstream of the bow shock for several weeks. Between about 99 and 62 Jupiter radii (R_J) a total of five crossings of the bow shock and three crossings of the magnetopause were identified in the plasma wave data. At the magnetopause, a new type of electrostatic noise was observed with characteristics similar to those of Earth's magnetopause. Within the magnetosphere continuum radiation trapped in the magnetospheric cavity, electrostatic waves at half-integral harmonics of the electron gyrofrequency, narrowband emissions at the upper hybrid resonance frequency, and whistler-mode chorus and hiss emissions were detected. On the outbound leg through the predawn tail region, strong low-frequency bursts of continuum radiation, modulated by the rotation of Jupiter, were observed; these observations indicated that the spacecraft entered regions of extremely low plasma density, ~ 1.0×10^{-5} cm^{-3}, apparently similar to the tail lobes of Earth's magnetosphere. We present here a survey of the initial results from the Voyager 2 plasma wave instrument, with emphasis on the new observations and comparisons with the Voyager 1 results. The data base for the present discussion starts with the first detection of radio emissions from Jupiter about 6 months before closest approach and ends