Reports

Voyager 2 Encounter with the Jovian System

Abstract. *An overview of the Voyager 2 encounter with Jupiter is presented, including a brief discussion of the trajectory, the major sequence modifications performed because of the Jupiter measurements obtained with Voyager 1, and highlights of the results that are described in the subsequent reports.*

The Voyager 2 encounter with Jupiter was the second step in the NASA Voyager Program of exploration of the outer planets. Launched on 20 August 1977, Voyager 2 arrived at Jupiter just 18 weeks after the successful Voyager 1 flyby (*1*). Voyager 2 began extensive Jovian measurements on 25 April 1979, encountered Jupiter at the closest approach distance of 721,670 kilometers at 22:29.0 UTC (Universal Time, coordinated) 9 July 1979, and completed its principal measurements of Jupiter's environment on 5 August 1979. Throughout this 103-day period, nearly continuous measurements were obtained from the Jovian system and the nearby interplanetary medium, enabling a number of discoveries to be made and providing additional information on the Voyager 1 studies.

The Voyager 2 scientific investigations and instruments are listed in Table 1. The location of the instruments and the essential characteristics of the spacecraft were given in the Voyager 1 Jupiter report (*1*).

The timing of the Jupiter encounter was chosen so that the Voyager 2 encounter with Saturn would occur during a period when the planetary positions would permit the spacecraft to swing by Saturn and continue toward a Uranus encounter in 1986. This arrival date also resulted in a larger flyby distance at Jupiter with a correspondingly lower radiation dose than Voyager 1 received from the intense radiation nearer the planet.

The specific Voyager 2 encounter trajectory was chosen to complement that of Voyager 1. A view of the Voyager 2 trajectory through the Galilean satellite system is shown in Fig. 1, which covers ± 44 hours around closest approach to Jupiter. Special characteristics of the Voyager 2 trajectory are: (i) a close approach to Europa, which was observed only at a great distance from Voyager 1; (ii) close approaches to Ganymede and Callisto prior to Jupiter closest approach, thus providing a high resolution view of the opposite faces from those observed by Voyager 1; (iii) an outbound direction that allowed the deepest penetration to date of the Jovian magnetotail (see Fig. 2); (iv) Earth and sun occultations which probe the south polar Jovian atmosphere for comparison with the equatorial occultations by Voyager 1; and (v) a higher approach latitude to provide a different view of the latitude-de-

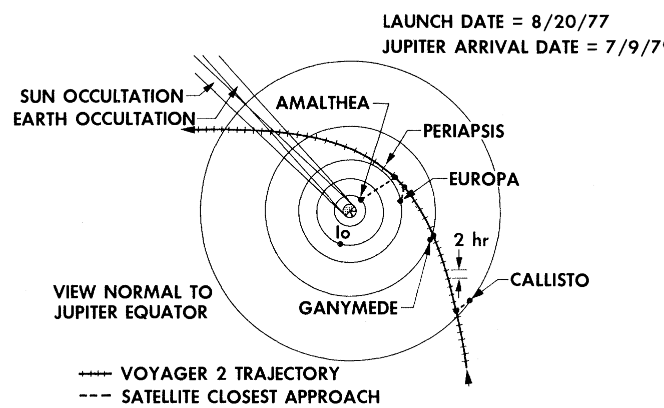

Fig. 1. Voyager 2 Jupiter encounter geometry. This view from the planet north pole shows the trajectory closest approach geometry to the planet and selected satellites, 2-hour time interval tick marks along the trajectory path, and Earth and sun occultation zones through which the spacecraft flies. The actual closest approach distances are listed in Table 2.

Table 1. Scientific investigations for the Voyager mission.

Investigation*	Abbreviation	Typical Jovian encounter objectives
Imaging science (B. A. Smith)	ISS	High-resolution reconnaissance over large phase angles; atmospheric dynamics; geologic structure of satellites
Infrared radiation (R. A. Hanel)	IRIS	Atmospheric composition, thermal structure, and dynamics; satellite surface composition and thermal properties
Photopolarimetry (C. W. Hord)	PPS	Atmospheric aerosols; satellite surface texture and sodium cloud
Radio science (V. R. Eshleman)	RSS	Atmospheric and ionospheric structure, constituents, and dynamics
Ultraviolet spectroscopy (A. L. Broadfoot)	UVS	Upper atmospheric composition and structure; auroral processes; distribution of ions and neutral atoms in the Jovian system
Magnetic fields (N. F. Ness)	MAG	Planetary magnetic field; magnetospheric structure; Io flux tube currents
Plasma particles (H. S. Bridge)	PLS	Magnetospheric ion and electron distribution; solar wind interaction with Jupiter; ions from satellites
Plasma waves (F. L. Scarf)	PWS	Plasma electron densities; wave-particle interactions; low-frequency wave emissions
Planetary radio astronomy (J. W. Warwick)	PRA	Polarization and spectra of radio frequency emissions; Io radio modulation process; plasma densities
Low-energy charged particles (S. M. Krimigis)	LECP	Distribution, composition, and flow of energetic ions and electrons; satellite-energetic particle interactions
Cosmic-ray particles (R. E. Vogt)	CRS	Distribution, composition, and flow of high-energy trapped nuclei, energetic electron spectra

*The principal investigator or team leader is indicated in parentheses.

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Table 2. Selected Jovian and Voyager encounter parameters. Except as noted, the satellite physical data are from (4). Distances are to the center of mass, not to the body surface.

Body	Mean distance from Jupiter (10^3 km, R_J)*	Mean orbital period (days)	Mass (moon = 1)†	Closest approach distance (km) from	
				Voyager 1	Voyager 2
Jupiter			318.1‡§ (Earth = 1)	348,890	721,670
Amalthea (J5)	181.3, 2.54	0.489		420,200	558,370
Io (J1)	421.6, 5.90	1.769	1.21	20,570	1,129,900
Europa (J2)	670.9, 9.40	3.551	0.66	733,760	205,720
Ganymede (J3)	1070.0, 14.99	7.155	2.03	114,710	62,130
Callisto (J4)	1880.0, 26.33	16.689	1.45	126,400	214,930

*R_J = 71,398 km = Jupiter equatorial radius (5). †Mass of moon = 7.350×10^{22} kg (6). ‡Mass of Earth = 5.976×10^{24} kg (6). §Mass of Jupiter = 1.901×10^{27} kg (5).

pendent radio emissions observed by Voyager 1. Important characteristics of the two Voyager trajectories are summarized in Table 2, which also contains some relevant parameters of the Jovian system (2). Together Voyager 1 and 2 establish a 7-month time base for the study of atmospheric dynamics and an even longer time base for Io plasma torus studies.

In order to derive additional information on some of the Voyager 1 discoveries, a number of changes were made to the preplanned Voyager 2 sequences (3). For example, a number of image sequences of the Jovian ring system were inserted into the timeline to determine the radial extent of the ring, and a 10-hour period of repetitive imaging of Io was added in order to search for any short-term variations in the volcanic plumes. In addition, ultraviolet scans of the Jovian auroral regions were modified so that the region of maximum activity could be accurately determined, infrared observations of the polar regions were modified to optimize the study of global distribution of ethane and acetylene, and more high-rate plasma wave and radio measurements were scheduled for lightning and other studies. Other modifications included several additional rolls of the spacecraft for plasma studies, a redesign of the ultraviolet observations of the Io torus in order to record any temporal variations, and the addition of a stellar occultation of Jupiter for study of the upper atmosphere.

Both the originally planned sequences and the subsequent modifications had to take into account the presence of a backup mission load in one-half of one of the two sequencing memories. This minisequence for spacecraft and science data acquisition at Saturn was designed to automatically take control should the failure of the single remaining command receiver prevent the spacecraft from receiving further sequencing instructions from Earth (the other command receiver failed during the preencounter cruise period). The design and duration of the originally planned sequences and their uplinking to the spacecraft also had to take into account the fact that the failure of a component had increased the sensitivity of the remaining command receiver to thermal changes and radiation dose. The impact of these constraints on the scientific return from Voyager 2 was minimized by careful design and implementation of the sequences and by the development and execution of appropriate operational procedures.

Like Voyager 1, Voyager 2 returned data on a broad range of scientific studies as discussed in the following reports. The Voyager 2 encounter has not only provided additional details about a number of the Voyager 1 discoveries but has also enabled additional discoveries to be made. Some highlights from the subsequent reports are as follows.

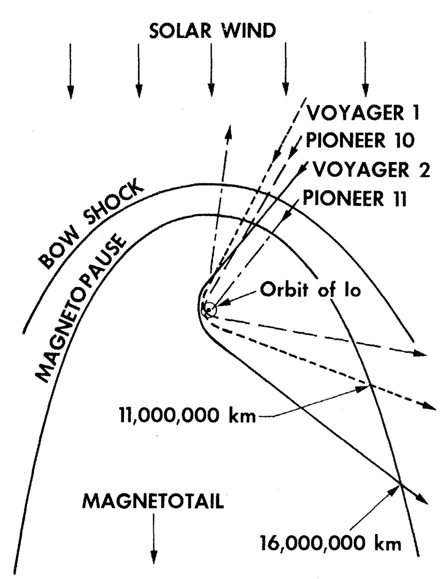

Fig. 2. North polar view of the Jovian magnetosphere region. The trajectories of the four Pioneer and Voyager spacecraft that have examined Jupiter are shown for a fixed bow shock and magnetosphere configuration. All four spacecraft have sampled the sunward bow shock and magnetosphere region at various latitudes, but only limited magnetotail probing has occurred, with Voyager 2 remaining in the tail for the greatest distance from Jupiter.

Atmosphere

The main atmospheric jet streams were present during both Voyager encounters, with some change in velocity.

The Great Red Spot, the white ovals, and the smaller white spots at 41°S appear to be meteorologically similar.

The formation of a structure east of the Great Red Spot formed a barrier to the flow of small cloud vortices which earlier were circulating about the Great Red Spot.

The ethane (C_2H_6) to acetylene (C_2H_2) abundance ratio appears to be larger in the polar regions than at lower latitudes and appears to be 1.7 times higher on Voyager 2 than on Voyager 1.

Thermal maps at ~150 and ~800 millibars of atmospheric depth exhibit both local and large-scale structure and suggest the importance of dynamical heating and cooling processes.

A map of Jupiter at 2400 Å shows the distribution of ultraviolet absorbing haze. The polar regions are surprisingly dark, suggesting absorbing material must be above the 40-millibar level.

Equatorial ultraviolet emissions indicate planet-wide charged particle precipitation.

The high-latitude ultraviolet auroral activity occurs on the magnetic field lines which thread the plasma torus.

Ionospheric temperatures in the south polar region were 1200 K and 1600 K, the latter being the highest topside plasma temperature observed at Jupiter.

Satellites and Ring System

The ring consists of a bright, narrow segment surrounded by a broader, dimmer segment ~5800 km wide.

Upper limits on the optical depth of the ring material range from 3×10^{-4} to 3×10^{-3} in the infrared.

The interior of the ring is filled with much fainter material that may extend down to the top of the atmosphere.

Images of Amalthea in silhouette against Jupiter indicate that the satellite may be faceted or diamond shape.

Volcanic activity on Io had changed somewhat, with six of the plumes observed by Voyager 1 still erupting.

The largest Voyager 1 plume had ceased, while the dimensions of another plume had increased by 50 percent.

Several large-scale changes in Io's appearance had occurred, consistent with surface deposition rates of 10^{-2} centimeters per year deduced for plume areas.

The surface of Europa is remarkably smooth with few craters and is probably 10^8 years or older.

The surface of Europa consists of slightly mottled terrain and uniformly bright terrain crossed by linear markings and ridges.

There are four basic terrain types on Ganymede, including younger, smooth terrain and a rugged impact basin that was observed by Voyager 2.

Callisto's entire surface, which is even more densely cratered in the hemisphere viewed by Voyager 2, must be some 4×10^9 years old.

Low latitude surface temperatures on the Galilean satellites range from 80 K (night) to 155 K (the subsolar point on Callisto).

Underneath a thin surface layer, the thermal inertia of Callisto is about twice that of the moon.

Magnetosphere

The outer region of the magnetosphere contains a hot plasma consisting primarily of hydrogen, oxygen, and sulfur ions.

The hot plasma generally flows in the corotation direction out to the boundary of the magnetosphere.

The plasma sheet, which inside of ~ 50 Jupiter radii (R_J) lies in the magnetic equatorial plane, is approximately parallel to the Jovian or the solar magnetosphere equatorial plane at greater tailward distances.

Between 18 and 25 R_J, the bulk velocity of the low energy plasma is lower than the corotation value.

Electron densities as low as $\sim 10^{-5}$ per cubic centimeter occur on the predawn taillike region of the magnetosphere.

Beyond ~ 160 R_J, the hot plasma streams nearly antisunward.

Outbound the spacecraft experienced multiple magnetopause crossings between 169 and 279 R_J.

The abundance of oxygen and sulfur relative to helium at ~ 1 MeV per nucleon increases with decreasing distance from Jupiter.

The phase space density gradient of higher energy oxygen (~ 6 MeV per nucleon) suggests that these nuclei are diffusing inward toward Jupiter.

At 10 R_J, the Jovian magnetic field intensity was significantly depressed (20 percent low) because of the immersion of Voyager 2 in the current sheet.

The ultraviolet emission from the Io plasma torus was twice as bright as 4 months earlier, and the temperature had decreased by 30 percent to 60,000 K.

The low frequency (kilometric) radio emissions (<1 MHz) from Jupiter have a strong latitude dependence with a narrow shadow zone near the magnetic equator.

The kilometric radiation often contains narrowband emissions that drift to lower or higher frequencies with time.

Intense narrowband emissions were observed that may be the source of continuum radiation trapped inside the magnetosphere.

A complex magnetosphere interaction with Ganymede was observed in the magnetic field, plasma, and energetic particles up to $\sim 200{,}000$ km from the satellite.

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References and Notes

1. A brief overview describing the Voyager spacecraft, its instrument complement, and the Voyager 1 trajectory at Jupiter can be found in *Science* **204**, 945 (1979); other Voyager 1 reports appeared in the same issue.
2. The new values of the satellite radii, as determined by Voyager 1 and 2, are given by B. A. Smith *et al.*, *Science* **204**, 951 (1979), B. A. Smith *et al.*, *ibid.* **206**, 927 (1979).
3. The sequencing aspect of the spacecraft operation is briefly described in (*1*).
4. D. Morrison *et al.*, *Introducing the Satellites, Planetary Satellites*, J. A. Burns, Ed. (Univ. of Arizona Press, Tucson, 1977), p. 6.
5. R. Smoluchowski, in *Jupiter*, T. Gehrels, Ed. (Univ. of Arizona Press, Tucson, 1976).
6. C. W. Allen, *Astrophysical Quantities* (Athlone, London, 1973).
7. The extraordinary scientific findings discussed in this issue of *Science* represent the culmination of many years of dedicated, tireless effort by a large number of people at all levels in numerous organizations. The scientists associated with the Voyager Project gratefully acknowledge the superb accomplishments of all these individuals. The Voyager Program is one of the programs of the Planetary Division of NASA's Office of Space Science. The Voyager Project is managed by the Jet Propulsion Laboratory of the California Institute of Technology under NASA contract NAS 7-100.

5 October 1979

The Galilean Satellites and Jupiter: Voyager 2 Imaging Science Results

Abstract. *Voyager 2, during its encounter with the Jupiter system, provided images that both complement and supplement in important ways the Voyager 1 images. While many changes have been observed in Jupiter's visual appearance, few, yet significant, changes have been detected in the principal atmospheric currents. Jupiter's ring system is strongly forward scattering at visual wavelengths and consists of a narrow annulus of highest particle density, within which is a broader region in which the density is lower. On Io, changes are observed in eruptive activity, plume structure, and surface albedo patterns. Europa's surface retains little or no record of intense meteorite bombardment, but does reveal a complex and, as yet, little-understood system of overlapping bright and dark linear features. Ganymede is found to have at least one unit of heavily cratered terrain on a surface that otherwise suggests widespread tectonism. Except for two large ringed basins, Callisto's entire surface is heavily cratered.*

Atmosphere of Jupiter: Introduction. Voyager 2's observations of Jupiter were carried out on a schedule similar to that successfully executed during the Voyager 1 encounter with Jupiter (*1*). Continuous global observations of the planet were made for a period of 63 days. The sequence began with a multicolored series of narrow-angle frames every 72° of longitude (observatory phase), then changed to one of periodic mosaics when the planet's image became too large to fit within the field of view of the narrow-angle camera. During the final 12 days of approach, selected areas of the planet were targeted for observations that could be used for studies of cloud morphologies and atmospheric motions. The combined Voyager 1 and 2 observations of Jupiter provide an almost continuous record, over a 6-month period, of the behavior of the Jovian atmosphere at a resolution far better than can be obtained from Earth-based studies. In this report we briefly describe the changes in the cloud morphologies and local atmospheric motions that have occurred in the Jovian atmosphere between the Voyager 1 (5 March) and Voyager 2 (9 July) encounters.

General appearance and average zonal velocities of the Jovian atmosphere. The Voyager observations show some significant changes in the cloud patterns within a period of only a few months. These changes are in marked contrast with the observations of the two Pioneer spacecraft (*2*) which, although separated by a period of 12 months, showed little change in the cloud structure. Earth-based studies, however, have shown that cloud structures vary significantly with periods of about 4 to 5 years and occasionally 1 year or less (*3*).