Reports

Voyager 1 Encounter with the Jovian System

Abstract. *An overview of the Voyager 1 encounter with Jupiter is presented, including a brief discussion of the characteristics of the spacecraft and trajectory and highlights of the results which are described in the subsequent reports.*

The Voyager Program is a major element of NASA's strategy for the exploration of the outer solar system. Objectives of the Voyager mission include exploratory investigations of the Jovian and Saturnian planetary systems and of the interplanetary medium from Earth to Saturn. There is also an extended mission option which will, if all goes well, provide the first flyby investigation of Uranus and interplanetary studies beyond 20 astronomical units. Comparative studies of these planetary systems will receive particular emphasis (*1*).

The Voyager 1 encounter with Jupiter, which is the subject of the following reports, is the first step in these studies. Voyager 1 was launched on 5 September 1977, 16 days after the launch of Voyager 2 which is on a lower-velocity, later-arriving Jupiter trajectory. Voyager 1 began substantive measurements of the Jovian system on 6 January 1979, encountered Jupiter at a closest approach distance of 348,890 km at 12:04.6 UTC (Universal Time, coordinated) 5 March 1979, and completed its detailed observations of Jupiter on 13 April 1979. During this 98-day period, nearly continuous measurements of the Jovian system and the nearby interplanetary medium were accomplished, providing data for testing current Jovian theories and models and for making new, unexpected discoveries.

Scientific studies at Jupiter can be organized into the general areas of the atmosphere, the satellites, and the magnetosphere, although it is clear from the following reports that there is a significant interaction among the three areas. Studies of the Jovian atmosphere focused on atmospheric dynamics, composition, structure, and magnetospheric effects (aurora), whereas the satellite studies emphasized both the comparative and detailed geology of the Galilean satellites. The magnetospheric studies addressed the source of Jovian radio emissions, the dynamical properties of the magnetospheric environment, and satellite-magnetosphere interactions.

The scientific investigations and instruments that were selected to provide a broad-based study are listed in Table 1. Their designs incorporated parameters that were known to be valid for Jupiter and Saturn at a reference point of 1973–1974, with some minor modifications to accommodate knowledge gained by the Pioneer 10 and 11 encounter with Jupiter and more recent ground-based astronomy (*1*). The location of the science instruments on the Voyager spacecraft is shown in Fig. 1.

Although the Voyager spacecraft, which is described in detail by Draper *et al.* (*2*), has evolved from previous Mariner-class spacecraft, the capability, complexity, and reliability of the spacecraft have been markedly increased in order to undertake a broad range of detailed scientific investigations over an extended time period. Certain of the spacecraft characteristics directly impact the scientific capabilities of the Voyager mission:

1) The three-axis stabilized spacecraft provides long integration time and selective viewing for spectroscopic remote sensing and imaging.

2) The multihundred-watt radioisotope thermoelectric generators provided at Jupiter > 445 W, which supports 106 W of scientific instrumentation and a high-power X- or S-band transmitter.

3) The X-band telemetry rate of up to 115.2 kilobits per second at Jupiter provides for the return of one image every 48 seconds and for 3600 bits per second of general science and engineering data.

4) The scan platform, which carries two vidicon cameras (ISS), the ultraviolet spectrometer (UVS), the infrared interferometer (IRIS), and the photopolarimeter (PPS), provides pointing control of 0.15° per axis (3σ), so that instruments with small fields of view can be accurately targeted over essentially the entire celestial sphere.

5) The three interconnected computer systems [the attitude and articulation control subsystem (AACS), the flight data system (FDS), and the computer command subsystem (CCS)] provide significant onboard capability to execute complex sequences, to perform data compaction, and to optimize the spacecraft for changes in operating conditions or characteristics.

The complex sequence of scientific observations and the associated engineering functions are automatically executed by the spacecraft under the control of an updatable program stored in the CCS by ground command. At appropriate times generated by the stored code, the CCS issues commands to the AACS for platform activity or spacecraft maneuvers; to the FDS for instrument configuration changes or telemetry rate changes; or to numerous other subsystems within the spacecraft for specific actions to occur. The two identical (redundant) 4096-word memories within the CCS contain both fixed routines (about 2800 words) and a variable section (about 1290 words) for reprogrammable sequencing functions. The use of macrocalls of a few words each in the science sequence section to act on the fixed routines creates a thousandfold increase in discrete command efficiency. A single 1290-word science sequence load can easily generate 300,000 discrete commands, thus providing significantly more sequencing capability than would be possible through ground commands. A 1290-word sequencing load in the CCS will control both the science and engineering functions of the spacecraft for a predetermined period lasting for 3/4 day at closest approach and for up to 100 days during cruise.

Each 1290-word program (or load) is built from specific science measurement units or engineering functions called links. Some links were used repeatedly in a looping cyclic (like a computer DO loop) to perform the same observation numerous times; other links that involved special measurement geometry or critical timing occurred only once. About 175 science links were defined for the Voyager 1 Jupiter encounter. It took almost 2 years to convert the desired science objectives and measurements first into links, then into a minute-by-minute timeline for the 98-day encounter period, and finally into the specific computer code which could be loaded into the CCS memory for that portion of the encounter time frame represented by a particular load. The total Voyager 1 Jupiter encounter period used 18 sequence memory loads, supplemented by about 1000 ground commands to modify the sequences because of changing conditions or calibration requirements.

Equally important to the spacecraft

0036-8075/79/0601-0945$00.50/0

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. F. Lillie)	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

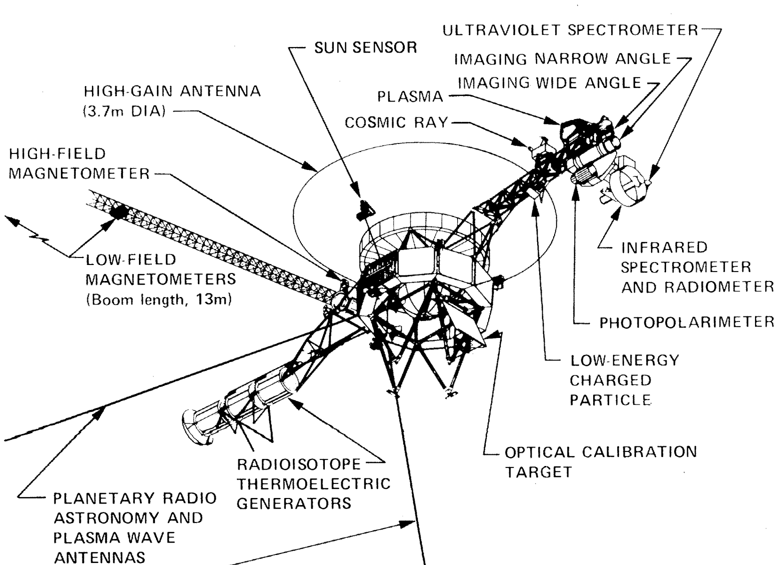
*The principal investigator or team leader is indicated in parentheses.

and sequence design was the design of the mission. The selection and design of the trajectories (*3*) for Voyager 1 and 2 were especially critical to accomplishing the scientific objectives. Important characteristics of the two Voyager trajectories are summarized in Table 2 which also contains some relevant parameters of the Jovian system (*4*).

A view of the Voyager 1 trajectory through the Galilean satellites is shown in Fig. 2 which covers the period of ± 32 hours around closest approach to Jupiter. Voyager 1 had its closest approach to each of the four Galilean satellites after periapsis with Jupiter. (Voyager 2 will be closest to Europa, Ganymede, and Callisto before perijove, will not have a close encounter with Io, and will remain outside Europa's orbit so as to receive much less radiation dose.) Special characteristics of the Voyager 1 trajectory at Jupiter are (i) periods of Earth and sun occultation to permit probing of the Jupiter atmosphere by radio waves and ultraviolet radiation, (ii) south polar passage by Io with an attempt to penetrate the postulated Io flux tube, (iii) reasonably close encounters with Ganymede and Callisto, and (iv) Earth-Jupiter communication distances that support maximum data rates for 21 to 22 hours each day.

In addition to the data acquisition around closest approach, remote sensing of Jupiter, the satellites, and the magnetosphere occurred many days before and after perijove. These studies provided measurements of the time variability of the Jovian atmosphere, the ion torus around Jupiter associated with Io, the large-scale geomorphology of the satellites, and the variability of the radio emissions in and around Jupiter. Special inbound and outbound maneuvers of the spacecraft provided data about the plasma and energetic particle flows in the magnetosphere.

To augment the normal attributes of a planetary encounter, several efforts were made to incorporate special ground-



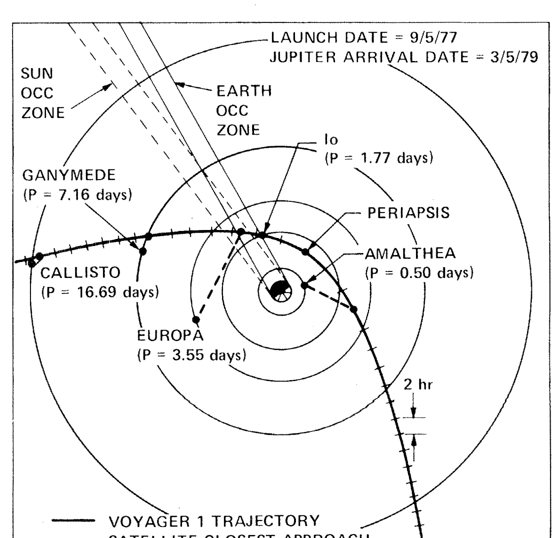


Fig. 1 (left). Voyager spacecraft. An advanced three-axis attitude stabilized spacecraft for exploration of the outer planets. The location of the science instruments on the spacecraft is noted. The optical calibration target is a specially coated plate used to provide flat-field illumination for ISS and PPS and a warm thermal body of known temperature for the IRIS. The scan platform, which contains these instruments, can be pointed to the plate. The spacecraft is usually oriented with the high-gain antenna directed toward Earth. The total spacecraft mass is approximately 825 kg. Fig. 2 (right). Voyager 1 Jupiter encounter geometry. This view from the planet north pole shows the trajectory closest approach geometry to the planet and selected satellites, satellite periods, 2-hour tick marks along the trajectory path, and the Earth and sun occultation zones through which the spacecraft flies. The actual closest approach distances are listed in Table 2. P is the satellite orbital period.

based astronomical observations. Visible wavelength studies of the large-scale Jupiter features, a continuing effort by several institutions, were intensified beginning around May 1978 and continued through the encounter period (*5*). Infrared studies were also given special attention because investigators wanted Voyager to target images and spectroscopic measurements to the 5-μm "hot spots" that have been detected from Earth. Supporting studies from Palomar and Mauna Kea provided data from which unique targets were identified and their drift velocities measured such that their location at encounter could be calculated (*6*).

Only two spacecraft problems arose during an otherwise near-perfect encounter. Prior to the start of encounter, the photopolarimeter experienced erratic analyzer wheel operation, and an element in the wheel drive motor circuitry failed about 6 hours before closest approach. The result was the loss of high accuracy photometry which would have provided the most quantitative data on Jupiter cloud heights and cloud particle size and shape. The second problem occurred in the most intense radiation environment when the time reference of the FDS shifted (~ 8 seconds total) causing synchronization of the FDS and CCS computers to change. This resulted in smearing of some of the Io and Ganymede images.

The Voyager 1 encounter with the Jovian system generated much new information about Jupiter's atmosphere, satellites, and magnetosphere. The subsequent reports in this issue place the Voyager encounter time frame in perspective with a long history of Jupiter atmospheric observations, and then discuss the preliminary findings of the Voyager investigations. Highlights of these investigations in the three areas of study are as follows.

Table 2. Selected Jovian and Voyager encounter parameters. Except as noted, the satellite physical data are from (*7*).

Body	Mean distance from Jupiter (10^3 km, R_J)*†	Mean orbital period (days)	Mass (moon = 1)‡	Closest approach distance from Voyager 1 (km)†	Planned approach distance from Voyager 2 (km)†
Jupiter			318.1§¶ (Earth = 1)	348,890	721,800
Amalthea (J5)	181.3, 2.54	0.489		420,200	558,600
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	205,800
Ganymede (J3)	1070.0, 14.99	7.155	2.03	114,710	62,300
Callisto (J4)	1880.0, 26.33	16.689	1.45	126,400	214,900

*R_J = 71,398 km = Jupiter equatorial radius (*8*). †Distance to the center of mass, not to the body surface. ‡Mass of moon = 7.350×10^{22} kg (*9*). §Mass of Earth = 5.976×10^{24} kg (*9*). ¶Mass of Jupiter = 1.901×10^{27} kg (*8*).

Atmosphere

Uniform velocities of features with widely different scales, suggesting that mass motion and not wave motion is being observed.

Rapid brightenings, followed by spreading of cloud material, perhaps the result of disturbances which trigger convective activity.

A belt-zone pattern of east-west winds in the polar regions, which were previously thought to have been dominated by convective upwelling and downwelling.

Anticyclonic motion of material associated with the Great Red Spot, with a rotational period of ~ 6 days.

Interactions of smaller spots, both with the Great Red Spot and with each other.

Auroral emissions in the polar regions, both in the ultraviolet (which were not present during the 1973 Pioneer encounter) and in the visible.

Cloud-top lightning bolts, similar to terrestrial superbolts.

A temperature inversion layer in the stratosphere at the 35-mbar pressure level and a temperature of 160 K at 5 to 10 mbar.

Up to 20 kilorayleighs of ultraviolet emission from the disk, indicating a thermospheric temperature of $\gtrsim 10^3$ K and an eddy diffusion coefficient $\lesssim 10^6$ square centimeters per second.

A break in the dayside ionospheric profile, which was not observed by Pioneer 10, suggesting there may be large temporal or spatial changes.

A volume fraction of helium in the atmosphere of 0.11 ± 0.03 [n(He)/n(H_2)].

A substantially colder atmosphere above the Great Red Spot than in the surrounding regions.

Satellites and Ring

Seven currently active volcanoes, probably driven by tidal heating, with plumes extending up to 250 km above the surface and eruption velocities up to 1 km sec^{-1}.

A large hot spot on Io which is ~ 150 K warmer than the surrounding surface and is associated with a volcanic feature.

Numerous intersecting, linear features on Europa, possibly due to crustal rifting or to tectonic processes.

Two distinct types of terrain, cratered and grooved, on Ganymede, suggesting that the entire ice-rich crust has been under tension due to global tectonic processes.

An ancient, heavily cratered crust on Callisto, with vestigial rings of enormous impact basins since erased by flow of the ice-laden crust.

The elliptical shape of Amalthea (265 × 140 km), which is about ten times larger than Phobos.

A ring of material about Jupiter, with an outer edge 128,000 km from the center of the planet and a thickness of $\lesssim$30 km.

Magnetosphere

An electrical current of ~ 5×10^6 A flowing in the magnetic flux tube linking Jupiter and Io.

Ultraviolet emissions from S^{2+}, S^{3+}, and O^{2+} in the Io plasma torus, indicating a hot (10^5 K) plasma which evidently was not present at the time of the Pioneer 10 encounter (December 1973).

Plasma electron densities exceeding 4500 cm^{-3} in some regions of the Io plasma torus.

A cold, corotating plasma inside of ~ 6 R_J, with ions such as O^+, O^{2+}, S^{2+}, and S_2^+ or SO_2^+.

High-energy ($\geq$ 7 MeV per nucleon) trapped particles inside ~ 6 R_J with significantly enhanced abundances of oxygen, sodium, and sulfur.

Hot plasma near the magnetopause predominantly composed of protons, oxygen, and sulfur.

Kilometric (10 kHz to ~ 1 MHz) Jovian radio emission, which may be generated by plasma oscillations in the Io plasma torus.

Corotating plasma flows in the dayside outer magnetosphere.

Enhanced trapped fluxes in the active hemisphere.

Evidence suggesting a transition from closed magnetic field lines ($\lesssim$ 25 R_J) to a Jovian magnetotail.

Continuum radiation trapped in the magnetosphere, permitting the determination of an electron density profile ranging from 4×10^{-4} cm^{-3} to 0.4 cm^{-3} in the distant magnetosphere.

Whistler emission, which is interpreted as lightning whistlers from the Jovian atmosphere.

Extensive radio spectral arcs (~ 1 to > 30 MHz), occurring in patterns correlated with Jovian longitude.

E. C. STONE
California Institute of Technology, Pasadena 91103

A. L. LANE
Jet Propulsion Laboratory, California Institute of Technology, Pasadena 91103

References and Notes

1. For an extensive discussion of the spacecraft, mission design criteria, trajectory selection, and the scientific investigations, see *Space Sci. Rev.* **21**, 75 (1977); *ibid.*, p. 75.
2. R. F. Draper, W. I. Purdy, G. Cunningham, "The Outer Planet Mariner Spacecraft," paper No. 75-1155, presented at the AIAA/AGU Conference on the Exploration of the Outer Planets, St. Louis, Mo., 1975.
3. C. E. Kohlhase and P. A. Penzo, *Space Sci. Rev.* **21**, 77 (1977).
4. The new values of the satellite radii, as determined by Voyager 1, are given by B. A. Smith *et al.*, *Science* **204**, 951 (1979).
5. R. J. Terrile and R. F. Beebe, *ibid.*, p. 948.
6. R. J. Terrile. R. W. Capps, D. E. Backman, E. E. Becklin, D. P. Cruikshank, C. A. Beichmann, R. H. Brown, J. A. Westphal, *ibid.*, p. 1007.
7. D. Morrison, *et al.*, *Introducing the Satellites, Planetary Satellites*, J. A. Burns, Ed. (Univ. of Arizona Press, Tucson, 1977), p. 6.
8. R. Smoluchowski, in *Jupiter*, T. Gehrels, Ed. (Univ. of Arizona Press, Tucson, 1976).
9. C. W. Allen, *Astrophysical Quantities* (Athlone, London, 1973).
10. 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 part of NASA's Office of Space Science, Lunar and Planetary Exploration Program. The Voyager Project is managed by the Jet Propulsion Laboratory of the California Institute of Technology under NASA contract NAS 7-100.

23 April 1979

Summary of Historical Data: Interpretation of the Pioneer and Voyager Cloud Configurations in a Time-Dependent Framework

Abstract. *Ground-based imaging of Jupiter at visible and infrared wavelengths has been used to build up a time sequence of cloud feature variations. The global cloud configuration seen by Voyager 1 appears markedly different than that seen by Pioneer 10 and 11. In the context of historical data, these two different cloud distributions are not unique but part of a continuous spectrum of global variations. The most recent global changes occurred in a pattern which has been a characteristic trend observed many times before.*

Jupiter has long been known to display large-scale variations in its visible appearance. The Voyager 1 encounter with Jupiter was, in effect, a snapshot of a planet constantly changing from one global cloud configuration to another. In this report we attempt to put this brief view into the historical perspective of what was known previously from ground-based monitoring at visible and infrared wavelengths. We will also describe the data base and preparation which went into the target selection for the Voyager imaging and infrared radiation (IRIS) experiments.

Designed into the Voyager 1 Jupiter encounter was a capability for targeting experiments to specific regions of high scientific interest. A Target Selection Working Group (*1*) was organized to designate the regions to be targeted. Generally, targeting consisted of two tasks. First, specific features were selected as targets and, second, accurate predictions were made of the temporal stability of features and their position at the time of encounter. Because of Jupiter's dynamic atmosphere and the constraint that the final targeting input deadline was 1 month before encounter, this second task demanded a large effort. A coordinated program to integrate ground-based observations in the visible and 5-μm wavelengths was carried out during the past year (*2*), resulting in prediction maps showing the location of desirable features.

Jupiter's appearance in visible as well as 5-μm wavelengths has undergone several large-scale changes since the Pioneer 10 encounter (December 1973). We will relate these changes, in the context of historical observations (*3*), to the long-term dynamical aspects of the planet. We will discuss zonal cloud cover as well as specific morphology. For a more complete description of Jovian historical cloud morphology, see (*3*).

Variations in the visible. A comparison of cloud configurations of Jupiter at the time of Pioneer 11 (*4*) and Voyager 1 is shown in Fig. 1. The most obvious changes are the darkening of the South Equatorial Belt (SEB) surrounding the northern edge of the Great Red Spot (GRS) and the brightening of the region between 23° and 35°N zenographic latitude. During the past 75 years, albedo changes of this magnitude have occurred at intervals of 5 to 8 years, with recurrence of both the Pioneer and Voyager aspect. The manner in which the high albedo regions form and dissipate and the cloud-top temperatures derived from 5-μm imaging data (*5*) indicate the high albedo regions are clouds at a higher elevation which obscure the lower cloud decks.

Yearly comparisons of Jupiter photographs indicate that between 1973 and 1974 the positions of the most prominent belts and zones remained unchanged and the only color difference was the subtle loss (in 1974) of blue-gray color in the equatorial edge of the SEB. In 1975, the dark southern component of the SEB at about 12°S appeared in what was a very broad and featureless South Tropical Zone (STrZ). The area between the northern and southern components of the SEB to the east of the GRS appeared white and featureless, that is, zonelike. However, to the west of the GRS this same latitudinal band was dark gray in color and mottled. This appearance was part of a characteristic trend known as the SEB disturbance and has been observed many times before (*3*, *6*). The South Temperate Belt (STeB) at about 38°S, which was longitudinally homogeneous in 1973 and 1974, appeared to have broken up into small fragments in the 1975 apparition. Other changes apparent in 1975 were that the equatorward edge of the SEB regained its blue-gray color and the north edge of the North Equatorial Belt (NEB) acquired a conspicuous dark brown color. In 1976, the SEB disturbance completely obliterated the zone (that is, the STrZ) separating its northern and southern components. This very wide belt appears blue-gray on its north edge and brown to the south. The GRS lost most of its contrast because of its proximity to dark material surrounding the red spot and to a belt directly to the north. The NEB remained unchanged from the previous year but the STeB once again displayed a homogeneous appearance. In the period between 1976 to the present, Jupiter has displayed only very minor albedo variations. These changes were mainly a whitening of the STrZ into a very broad region between 17° and 35°N, and some small color differences in the region from the equator to 38°S.

In summary, the past 6 years of Jovian cloud activity have been characterized by color variations in all belts and by a major SEB disturbance resulting in the darkening of a large part of the STrZ.

Five-micrometer features. Yearly monitoring of Jupiter in the 5-μm window