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The Voyager Encounter With Neptune

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The Voyager Neptune/Interstellar Mission is the continuation of the NASA program of exploration of the outer solar system. The prior phases of the Voyager program included encounters with Jupiter, Saturn, and Uranus as summarized in the *Journal of Geophysical Research* (volume 86, pages 8121–8841, 1981; volume 88, pages 8625–9018, 1983; and volume 92, pages 14,873–15,375, 1987). Following the successes of these prior phases of the Voyager mission, a new phase was undertaken with the objectives of exploring the Neptune system and continuing the investigation of the interplanetary and interstellar media. An additional objective was to preserve the capability to extend the investigations to include a search for the heliopause. Summaries of results from the Neptune and Triton encounters are reported in the following papers.

All 11 scientific investigations listed in Table 1 made significant contributions to the exploration of the Neptune system. The characteristics of the corresponding instruments are summarized in Table 2, with more details available in *Space Science Reviews* (volume 21, pages 75–376, 1977). The five remote sensing instruments (the narrow- and wide-angle vidicon cameras, the infrared and ultraviolet spectrometers, and the photopolarimeter) are boresighted and mounted on a scan platform having two axes of articulation. The locations of the instruments on the spacecraft are shown in Figure 1.

The Voyager spacecraft were designed for the 4-year missions to Jupiter and Saturn, but both spacecraft continue to operate nearly flawlessly 14 years after launch. No further electronic or mechanical failures have occurred since the 1986 Uranus encounter. On-board computers continue to control the attitude of the spacecraft, to point the scan platform, to sequence the scientific and engineering events, to set the data formats and telemetry rates, and to operate the scientific instruments [*Draper et al.*, 1975]. The lower light levels and greater communications distances at Neptune were compensated by further slowing the average limit cycle rates of the spacecraft to reduce image smear and by improving the data-gathering capability of the ground receiving stations. Data smear was further reduced during the Neptune encounter by extensive utilization of image motion compensation techniques, both by rotating the entire spacecraft and by programming the scan platform to move slowly enough to track the rings, Neptune's limb, and Triton's limb near their closest approaches (see, for example, *Stone and Miner* [1989]).

Between the Uranus and Neptune encounters, an additional high-efficiency 34-m tracking station was added to the Madrid tracking complex, and the three 64-m tracking antennas were each enlarged to 70-m diameter and improved in efficiency. The Parkes (Australia) radio telescope aided the Canberra (Australia) complex in collecting data, and for the first time the twenty-seven 25-m antennas of the Very Large Array near Socorro, New Mexico, aided the Goldstone (California) complex. As a result, the quality and quantity of data collected during the Neptune encounter equaled or exceeded that collected during the Uranus encounter, despite the longer light time and weaker signal.

The trajectories of the two Voyager spacecraft are shown in Figure 2. Voyager 2 was launched from Cape Canaveral, Florida, on August 20, 1977, followed by Voyager 1 on September 5, 1977. The slower Voyager 2 trajectory was chosen to allow the option of using gravity assist at Saturn to continue to Uranus and Neptune. Voyager 1 close approaches to Jupiter and Saturn occurred on March 5, 1979, and November 12, 1980, respectively. Voyager 2 close approaches to Jupiter, Saturn, Uranus, and Neptune occurred on July 9, 1979, August 25, 1981, January 24, 1986, and August 25, 1989, respectively.

The Voyager 2 trajectory at Neptune is shown in Figure 3, with selected encounter distances listed in Table 3. The close approach of Neptune's north polar region enabled close magnetospheric measurements and a subsequent close approach to Triton. Passage through the Earth and Sun occultation zones of Neptune, the rings, and Triton was also achieved. The spacecraft passed through the Neptune ring plane both inbound and outbound.

The 11 scientific teams undertook a broad range of studies of the planet, the rings, the satellites (especially Triton), and

TABLE 1. Voyager Science Investigations

Investigation Team	Principal Investigator, Institution
Imaging (ISS)	B. A. Smith, University of Arizona
Photopolarimetry (PPS)	A. L. Lane, Jet Propulsion Laboratory
Infrared spectroscopy (IRIS)	B. J. Conrath, Goddard Space Flight Center
Ultraviolet spectroscopy (UVS)	A. L. Broadfoot, University of Arizona
Radio science (RSS)	G. L. Tyler, Stanford University
Magnetometry (MAG)	N. F. Ness, University of Delaware
Plasma (PLS)	J. W. Belcher, Massachusetts Institute of Technology
Low-energy charged particles (LECP)	S. M. Krimigis, Applied Physics Laboratory
Cosmic rays (CRS)	E. C. Stone, California Institute of Technology
Plasma waves (PWS)	D. A. Gurnett, University of Iowa
Planetary radio astronomy (PRA)	J. W. Warwick, Radiophysics, Inc.

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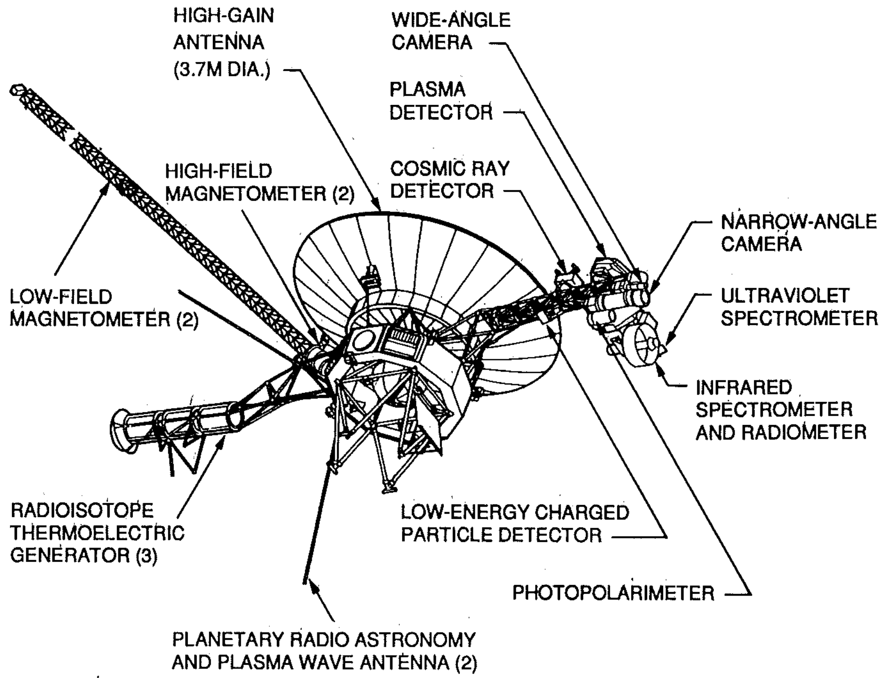

Fig. 1. A drawing of the Voyager spacecraft indicating the location of the science instruments and several spacecraft subsystems. The radio science investigation uses the spacecraft transmitters, an ultrastable oscillator, and the 3.7-m high-gain antenna.

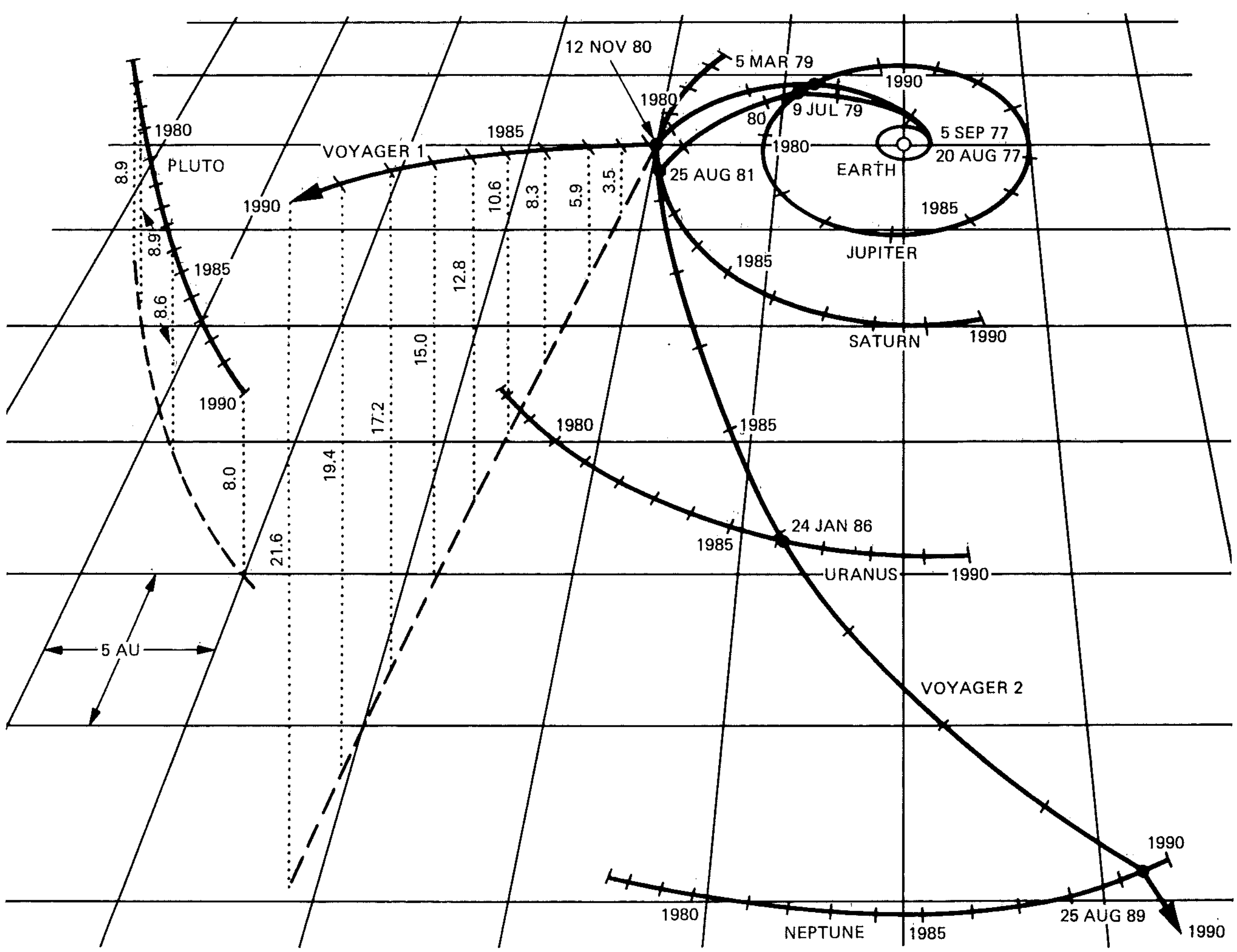

Fig. 2. A perspective view of the Voyager 1 and 2 trajectories from launch through the time of the Voyager 2 Neptune encounter.

TABLE 2. Typical Instrument Characteristics

Investigation	Nominal Characteristics
ISS	two Se-S vidicon cameras (f = 1500 mm and f = 200 mm); narrow-angle camera: 19 μrad per line pair, 2900–6400 Å
PPS	photomultiplier with 15-cm telescope; 2630–7500 Å; 3.5°, 1.0°, 0.33°, and 0.12° FOVs; two linear polarizers
IRIS	Michelson interferometer (3.3–50 μm) and radiometer (0.33–2 μm); 51-cm telescope; 0.25° FOV
UVS	grating spectrometer; 500–1700 Å with 10-Å resolution; airglow (1° × 0.1° FOV) and occultation (1° × 0.3° FOV)
RSS	S band (2.3 GHz) and X band (8.4 GHz); ultrastable oscillator ($<4 \times 10^{-12}$ short-term drift)
MAG	two low-field ($<10^{-6}$–0.5 G) and two high-field ((5×10^{-4})–20 G) sensors; 13-m boom; 0–16.7 Hz
PLS	Earth-pointing sensor (10-eV to 6-keV ions) and lateral sensor (10-eV to 6-keV ions; 4-eV to 6-keV electrons)
LECP	two solid-state detector systems; rotating platform; 10- to 10,000-keV electrons; 10- to 150,000-keV/nucleon ions
CRS	multiple solid-state detectors; 3- to 110-MeV electrons; 1- to 500-MeV/nucleon nuclei; three-dimensional anisotropies
PWS	sixteen channels (10 Hz to 56.2 kHz); waveform analyzer (150 Hz to 10 kHz); share PRA antennas
PRA	stepping receiver (1.2 kHz, 20.4 kHz to 40.5 MHz); right/left circular polarization; two 10-m monopole antennas

FOV is field of view.

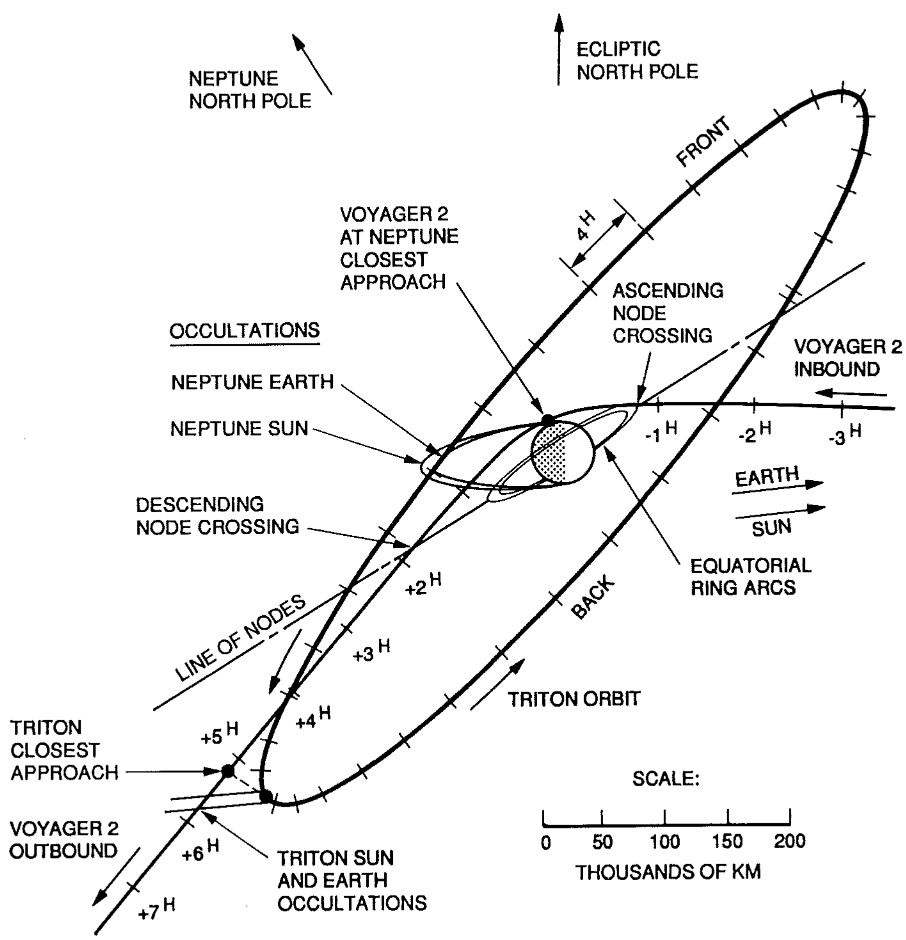

Fig. 3. A view normal to the trajectory plane of the Voyager 2 path through the Neptune system.

TABLE 3. Selected Neptune Encounter Characteristics

Body or Event	Closest Approach, km	UT, August 25, 1989
Nereid	4,652,880	0006.6
Inbound ring crossing	85,290	0253.0
Neptune	29,240	0355.7
Outbound ring crossing	103,950	0514.8
Triton	39,790	0910.1

the magnetosphere. Planning for these studies benefited greatly from the Earth-based observations and theoretical analyses summarized at and subsequent to a Uranus/Neptune workshop held in Pasadena, California, in February 1984 [*Bergstralh*, 1984]. The initial reports of the Voyager 2 studies of Neptune, which were published in *Science* (volume 246, pages 1417–1501, 1989), have been followed by much more detailed studies, many of which are reported in the following papers. Studies of the Neptune data should continue for many years, since the Voyager 2 data are unlikely to be superseded for several decades.

The Voyager program is now in its final phase, the Voyager Interstellar Mission. Both spacecraft continue to search for the heliopause. Voyager 1 is headed toward right ascension/declination of 262°/+12° at a rate of 3.50 AU per year relative to the Sun; Voyager 2's direction and rate are 338°/−62° and 3.13 AU per year, respectively. Voyager 1 should reach a heliocentric range of 100 AU in the year 2006, and Voyager 2 in 2012. Both spacecraft are expected to continue operating, barring catastrophic failures, until at least the year 2015.

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