Voyager 2 and the world of Neptune

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After dramatic discoveries during its flybys of Jupiter, Saturn and Uranus, *Voyager 2* has now sent back breath-taking images of Neptune and its moons. The major discoveries in the Neptunian system include puzzling weather systems, broad sheet of ring material, peculiar offset and tilting of the magnetic dipole field, six new moons, and atmospheric composition and surface features of the biggest moon, Triton.

INTRODUCTION

THE *Voyager* odyssey is a truly remarkable example of the spirit of human exploration and adventure. *Voyager 2* and its sister spacecraft, *Voyager 1*, during their historic journey in the last 12 years, have provided an amazingly new view of the three giant planets, Jupiter, Saturn and Uranus, 40 of their moons, and their unique systems of rings and magnetic fields as well as interplanetary magnetic fields and particles, and ultraviolet sources among the stars. They have thus brought about a qualitative change in our understanding of the outer planets of the solar system. The Neptune encounter of *Voyager 2* represents a befitting culmination of these earlier spectacular scientific achievements.

Although described occasionally as being slightly 'arthritic' (due to a partial failure of the scan platform actuator during Saturn encounter, thereby limiting it to only low rate slewing) and a little 'hard of hearing' (due to the failure of the main command receiver shortly after launch and limited tone reception capability of the backup receiver), *Voyager 2* performed flawlessly during its most recent encounter with Neptune and its largest moon, Triton.

Astronomers had noted in the early nineteenth century that Uranus, discovered by William Herschel in 1781, was not faithfully following its predicted orbit around the Sun. They speculated that this might be due to the gravitational pull of an unknown planet. Two mathematicians, John C. Adams of England and Jean J. U. Le Verrier of France, independently predicted (in 1845 and 1846 respectively)[1] the location of the eighth planet. Le Verrier sent his predictions to Johann G. Galle of the Berlin observatory who began a search for the object immediately. Within an hour of his telescopic search, Galle discovered an unidentified disk, only about a degree away from Le Verrier's and a few degrees away from Adams' prediction. The next night he confirmed the discovery of the new planet.

Neptune is the eighth and currently the farthest planet from the Sun and the fourth largest. Pluto in its highly eccentric orbit moved closer to the Sun than Neptune in early 1979, and will continue in this relative position till early 1999. At a distance of nearly 4.8 billion kilometres from the Sun, Neptune completes one orbit in 165 years. The planet has an equatorial diameter of 49,600 km and a polar diameter of 48,600 km. It is nearly four times larger than Earth and only slightly smaller than Uranus. Yet it weighs about 10.5 Earth masses while Uranus weighs only 8.7 Earth masses. This is because Neptune has an average density of $1.66\ \mathrm{g\,cm^{-3}}$, compared with the Uranian density of $1.19\ \mathrm{g\,cm^{-3}}$. This suggests that Neptune has more rock and less hydrogen, helium and other gases than does its sister planet. The inner core consisting of a mixture of rocks and ices is estimated to have a diameter of 16,000 km. A mantle made up mostly of liquid ammonia, liquid methane and water ice surrounds the core. The Neptunian atmosphere contains hydrogen, helium, methane and ethane, the latter two gases being responsible for the absorption of red wavelengths from sunlight and giving a blue-green colour to the planet.

THE ERA OF *VOYAGER*

The *Voyager 1* and *Voyager 2* missions[2], meant to explore the giant planets of the outer solar system, were born out of a concept known as the 'Grand Tour', which essentially involved taking advantage of the geometric alignment of the outer planets in the late 1970s. This arrangement of the outer planets, viz. Jupiter, Saturn, Uranus and Neptune, which occurs once in about 176 years, would allow a properly pointed spacecraft to swing from one planet to the next without using large spacecraft propulsion systems. In other words, the gravity assist provided by each of the planets would bend the flight path of the spacecraft and increase its velocity sufficiently to enable it to reach the next destination. At the time of the last alignment, Neptune had not yet been discovered. The next alignment of the planets will occur about the year 2152.

Voyager 1, launched on a faster and shorter trajectory compared to *Voyager 2* on 5 September 1977, encountered Jupiter on 5 March 1979 and Saturn on 12 November 1980. Geometric constraints prevent a spacecraft making a close flyby of Saturn's moon Titan from making similar flybys of Uranus or Neptune subsequently. In taking *Voyager 1* to the proximity of Saturn's rings and Titan, its flight path was bent sharply northward out of the ecliptic plane. Presently *Voyager 1* is heading away from the solar system at an angle of about 35 degrees above the ecliptic. This spacecraft may cross the heliopause, the boundary between the Sun's magnetic influence and interstellar space, by the next century. *Voyager 2*, launched on 20 August 1977, encountered Jupiter on 9 July 1979 and Saturn on 25 August 1981. In order to enable *Voyager 2* to make flybys of Uranus and Neptune, it was targeted to a suitable point at Saturn that would automatically take the spacecraft to these outer planets (figure 1).

At Jupiter *Voyager 1* and *Voyager 2* discovered active volcanoes on the satellite Io, thin rings of dust encircling the planet, and four new moons. At Saturn *Voyager 1* determined the composition of the large Saturnian moon Titan. Titan's atmosphere was found to be primarily of nitrogen, but also containing simple organic compounds that might have evolved into living organisms if Titan was not so cold. Several moons were discovered. Saturn's rings were found to be dynamic, with thousands of tiny wave-like features, perhaps electrically charged dust particles levitated above the ring plane. Wind velocity at the cloud-tops was measured at about 1600 km/h, about twice that on Jupiter. At Uranus *Voyager 2* found a strange magnetic field with a corkscrew-shaped tail extending millions of miles into space. It was

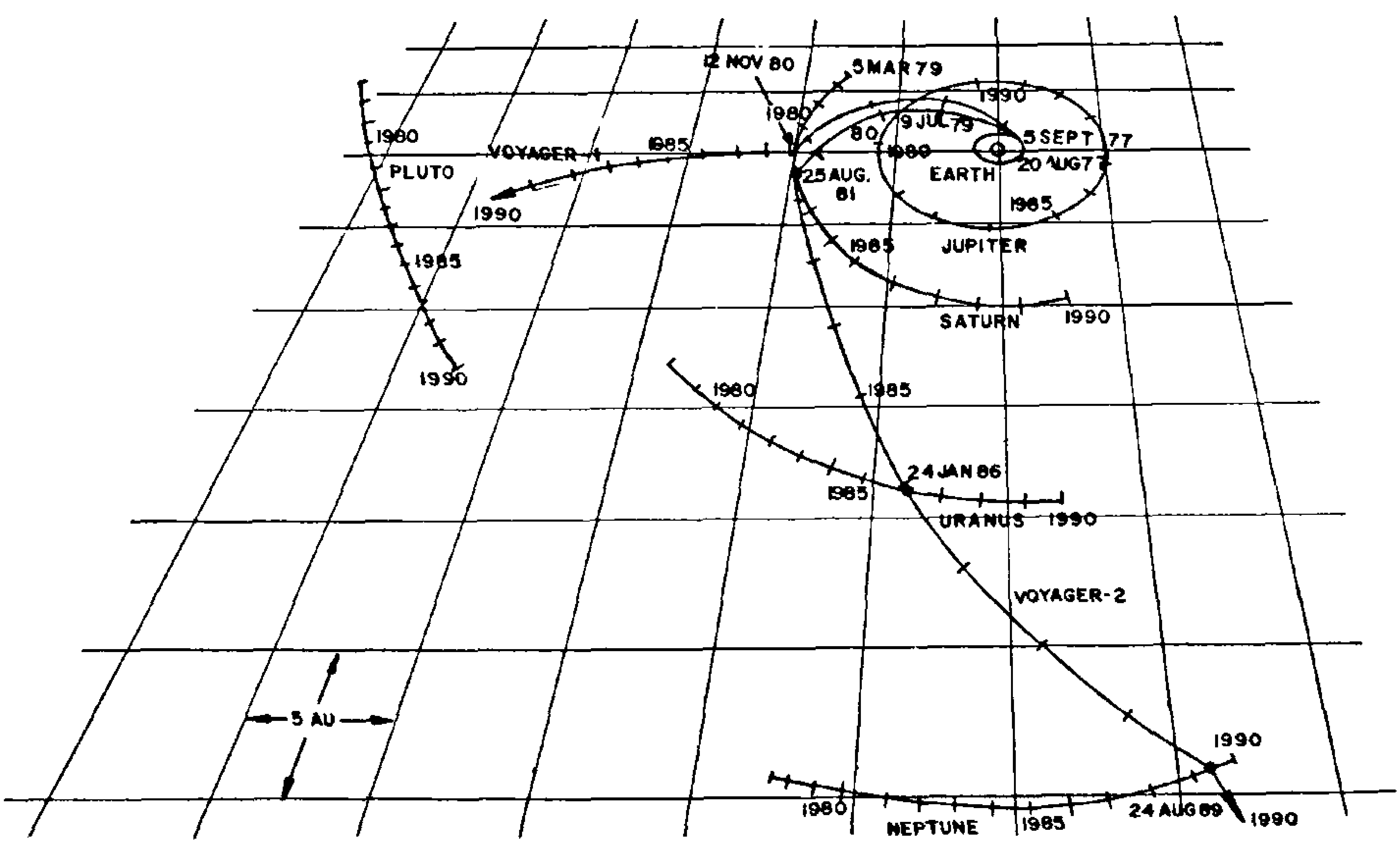

Figure 1. Trajectories of *Voyager 1* and *Voyager 2* with the dates of their encounters with planets.

Engineering adventure

Journey into Space: The first thirty years of space exploration, by Bruce Murray. W. W. Norton, New York, 1989, 381 pp., $19.95.

Bruce Murray is a professor at the renowned California Institute of Technology (Caltech). Just a few miles away is Jet Propulsion Laboratory (JPL), which started as a missile contractor for the US Army and is now owned and operated by Caltech. JPL became well known for its design of the *Explorer* satellite, which signalled the entry of the US into the space age. JPL is now a contractor for NASA, the US National Aeronautics and Space Administration. It has conceived, built and managed many spacecraft, including *Voyager 1* and *Voyager 2*. Bruce Murray was director of JPL when *Voyager 1* and *Voyager 2* were launched in 1977.

This book is the story of the remarkable deeds of a man and an organization, of their dreams and their struggles. Bruce Murray's dream has now become spectacular reality with *Voyager 2*'s rendezvous with Neptune.

We are told by the many reviews of the book in the American press that it is an inspiring book. Murray describes in great detail the working of JPL. He describes how NASA was never comfortable with the creative and independent JPL, which had the academic Caltech culture and eluded many governmental controls. Murray gives us a close view of the battles he fought and his courageous attacks of short-sighted government policies. To give an example, NASA had declared that the Space Shuttle should be the US's only launch system. Murray disagreed—not only because the Space Shuttle programme would take away most of the available funds—and insisted on development of alternative systems. The setback to the US space programme in the wake of the *Challenger* disaster and the inquiry into the disaster showed up the error of NASA's policy.

These are but a small part of a magnificent book, one that is full of engineering adventure. Murray's account of the rescue of a nearly failed spacecraft so that it could complete its mission reads like a Boys' Own adventure story to be read to be believed.

Murray tells us how he fell in love with Mars, which he first studied in 1960. Carl Sagan and he founded the Planetary Society, which now has a hundred thousand amateur astronomers as members. Now, Murray champions an international expedition to Mars in the next century.

Journey into Space is a story only a visionary and a pioneer can write, and one that must be read by anyone with even the slightest spirit of adventure. S. R.

inferred from such information that electrically conductive atmospheric layers must exist deep beneath the visible atmosphere of Uranus. Ten moons were discovered by *Voyager 2*. The close-ups of the Uranian moon Miranda showed the small satellite to be dramatically fractured by geophysical forces. Miranda was found to have one of the most geologically diverse landscapes seen in the solar system[3-7].

THE EXPERIMENTS ON *VOYAGER 2*

Voyager 2 carried onboard a bank of 11 scientific experiments[8] designed to investigate a variety of planetary phenomena Ten instruments are mounted on various locations of the spacecraft. The radio, used for communications with Earth, was also employed as a scientific instrument to probe planetary and satellite atmospheres (figure 2). The steerable scan platform of the spacecraft houses four instruments: the imaging science subsystem, infrared interferometer-spectrometer-and-radiometer, photopolarimeter and ultraviolet spectrometer.

Imaging science experiment

The experiment consists of two television cameras each with eight filters. The wide-angle camera has a

1. Cosmic ray detector
2. Plasma sensor
3. Wide angle imaging camera
4. Narrow angle imaging camera
5. UV spectrometer
6. IR spectrometer and radiometer
7. Photopolarimeter
8. Low energy charged particle detector
9. Antenna (3.7 M. dia.)
10. Hydrazine thrusters (16)
11. Spacecraft bus housing electronics
12. Planetary radio astronomy and plasma wave antenna
13. Nuclear thermoelectric generator
14. Magnetometers

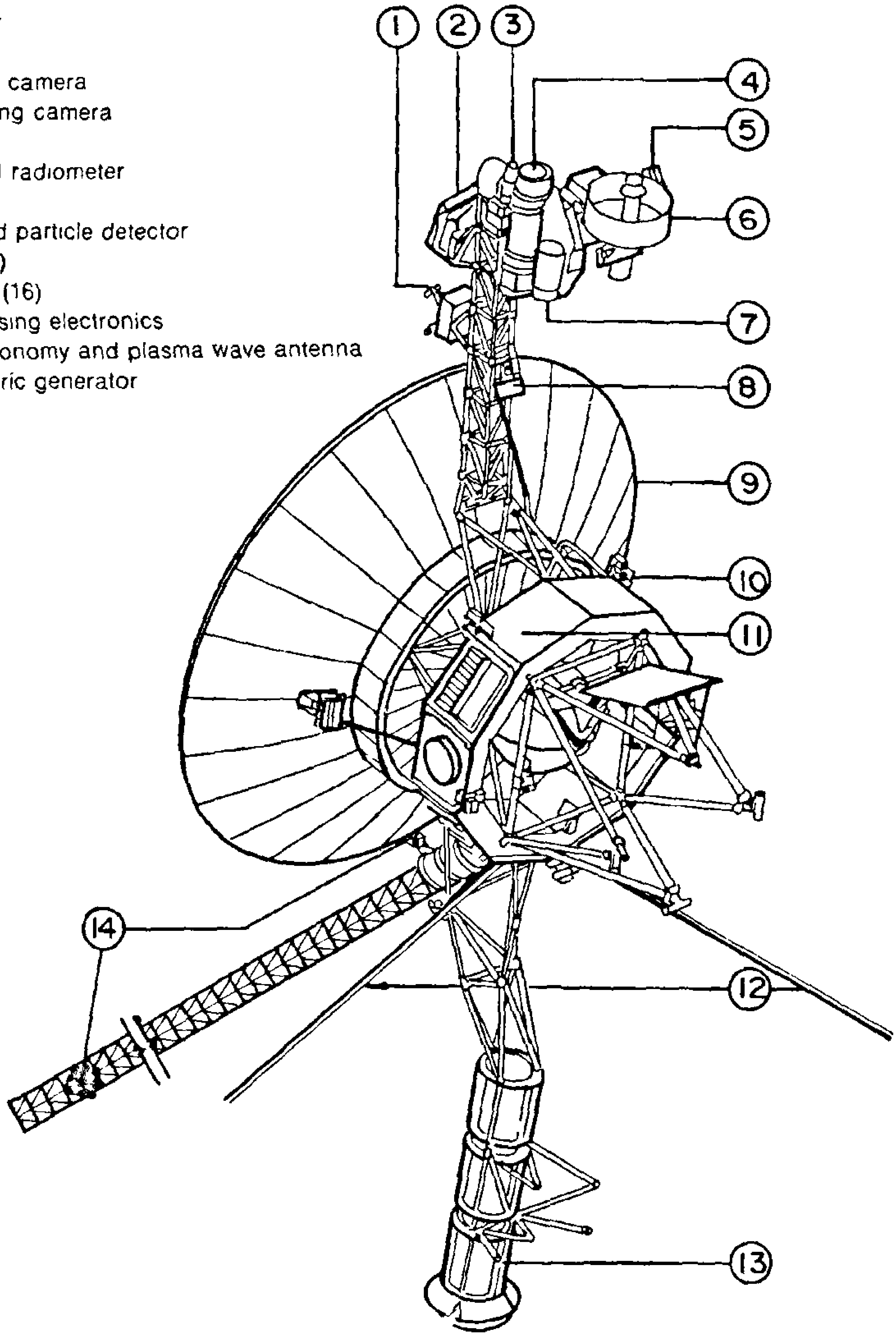

Figure 2. *Voyager 2* spacecraft, showing the location of different experimental subsystems.

focal length of 200 mm and images in the range 4000 to 6200 Å. The narrow-angle camera has a focal length of 1500 mm with an imaging range of 3200 to 6200 Å. This experiment will enable photographing visible characteristics of the Neptunian system, and conduct searches for new satellites and ring material.

IR interferometer-spectrometer-and-radiometer

This is a telescope-based system that measures radiation in two regions of the infrared spectrum, 2.5 to 50 μm and 0.3 to 2.0 μm. It can measure temperatures and determine certain types of elements or compounds present in the atmosphere or on a surface. As a radiometer, it can measure the total amount of reflected sunlight at UV, visible and IR frequencies.

Photopolarimeter

It consists of a (0.2 m) telescope fitted with filters and polarization analysers. It measures the way its targets reflect light and determines their properties, such as polarization. It covers eight wavelengths in the region between 235 μm and 750 μm. It is meant to study the surfaces of moons, tiny aerosol particles in an atmosphere, and ring particles. It can infer the texture and composition of a solid surface, the density, particle sizes and composition of a planetary ring, as well as particle sizes and composition of particle hazes. It is also usable for observing stellar occultations.

Radio science experiment

Here the two-way radio communications link with Earth is used to conduct scientific investigations. Precise measurements of the phase and amplitude of the radio signal reaching the Earth through the atmosphere of planet and satellites are analysed to detect minute variations. It can thus probe both planet and satellite atmospheres and ionosphere if present. Studies of solar corona and characterization of ring structures around the planet are also possible.

Ultraviolet spectrometer

It consists of a grating spectrometer sensitive to UV radiation in the range 500 to 1700 Å and uses the principle of atomic emission and absorption. It enables the study of the composition of the atmospheres of Neptune and Triton and can also be used for UV astronomy studies by observing stellar objects.

Cosmic ray experiment

It has seven independent solid-state-detector telescopes and together they cover the energy range 0.5 to 500 MeV. It can measure the energy spectrum of electrons and cosmic ray nuclei.

Low-energy charged particle detector

Consisting of two solid-state detectors mounted on a rotating platform, the experimental sensitivity ranges from 15 keV to about 160 MeV. The two subsystems, one a low-energy particle telescope and the other a low-energy magnetospheric particle analyser, are used to characterize the composition, energies and angular distribution of charged particles in interplanetary space and within planetary systems.

Magnetometer experiment

It has 4 magnetometers to detect and measure magnetic fields. Two are low-field instruments mounted on a 10 m boom away from the field of the spacecraft, while the other two are high-field instruments mounted on the body of the spacecraft. The low-field magnetometers can detect fields as weak as 1/10000 of the strength of Earth's magnetic field while the high-field instruments are designed to detect fields stronger than 20 times Earth's magnetic field. They are used to study the interaction of the magnetic field with moons orbiting within it and observe the interplanetary and interstellar magnetic fields in the vicinity of the planet.

Planetary radio astronomy experiment

It uses two 10 m electric antennas as detectors. This is shared with the plasma wave subsystem. The range covered is 20 kHz to 40.5 MHz in the radio frequency band. The experiment will search and characterize a variety of radio signals emitted by Neptune and determine the relationship of these emissions to the moons, the magnetic field, atmospheric lightning and plasma environment. Planetary and solar radio bursts will be measured from different directions in space and correlated with measurements made from Earth.

Plasma wave subsystem

This experiment is designed to measure the electric field component of local plasma waves. It uses the two extendable ion electric antennas, which stretch at right angles to one another forming a 'V', and covers the range 10 Hz to 56 kHz. It is used to measure the density and distribution of plasma, interactions of plasma waves with energetic particles and the interactions of moons and ring arcs with the planet's magnetosphere.

Plasma subsystem

This experiment consists of 2 plasma detectors sensitive to solar and planetary plasmas—both positive ions and electrons with energies between 10 and 6000 eV. One detector points in the direction of Earth and the other points at right angles to the first. It is used to study the extent and configuration of the magnetic field and the nature and sources of internal plasma and also to observe the solar wind and its interaction with the Neptune system.

VOYAGER 2 SPACECRAFT

The *Voyager 2* spacecraft (figure 2), with a launch mass of 825 kg, is nuclear-powered, consists of about 5 million electronic parts, and uses onboard computer fault detection and response to protect itself. The spacecraft structure is called a 'bus', which resembles a large ten-sided box with each side containing a compartment to house the scientific instruments. The spacecraft is usually aligned so that its roll axis (and thus the high-gain antenna) points to Earth.

The 3.66 m high-gain antenna transmits data to Earth on two frequency channels. The X-band at about 8.4 GHz contains the science and engineering data with downlink data rates ranging from 4.8 to 21.6 kbps. The other channel in the S-band around 2.3 GHz transmits only engineering data on the state of health of the spacecraft at low rates of 40 bps.

Spacecraft stabilization and spacecraft manoeuvering are controlled by an onboard computer called the attitude and articulation control system (AACS), which also controls scan platform motion. *Voyager*'s attitude is maintained by gyro control and celestial control using Sun sensor and Canopus star tracker. Gyro control is used for special purposes and short periods of time, up to several hours. Four of the science instruments which need to be pointed at a target body are on the scan platform. The scan platform has motors and gears (called actuators) which slew the platform to point in various directions.

Spacecraft electrical power ($\sim$400 W) is supplied from three radioisotope thermoelectric generators which employ plutonium 238 to generate heat, which in turn is converted to electrical energy.

On occasions when the antenna is not pointing at Earth or when the spacecraft is being manoeuvred or when the spacecraft is behind the planet as seen from Earth, the data are stored in a digital tape recorder.

The central controller of the spacecraft (CCS) consists of two identical computer processors, their software, algorithms and some associated electronic hardware. The main functions of the CCS are to carry out instructions from ground to operate the spacecraft, gather science data, and to be alert for and respond to any problem with any of the spacecraft subsystems.

THE ENCOUNTER WITH NEPTUNE

Even though Neptune is 4.5 billion kilometres from Earth, the actual trajectory, the Grand Tour route of *Voyager 2*, that finally took the spacecraft to the vicinity of Neptune, involved traversal of nearly 7 billion kilometres of interplanetary space. The trajectory for approach towards Neptune (figure 3) was tailored in such a way that *Voyager 2* had a modest velocity component in the same direction as Neptune's motion around the Sun. This velocity component of the spacecraft was trimmed to be nearly the same magnitude as Neptune's orbital speed, i.e. 468,000 km/day. These matched speeds kept both Neptune and *Voyager 2* from passing each other during most of the approach. In fact, the relative positions of the two were such that *Voyager 2* tended to stay close to the Sun–Neptune line, which gave its cameras and other sensors a nearly 'full moon' view of anything in the Neptune system—the planet, Triton, Nereid, and other possible moons yet to be discovered. These high-illumination lighting conditions gave the brightest view of the objects in the Neptune system and thus optimized the chances of discovering new objects in the system. The other velocity component, along the Sun–Neptune line, was over three times as fast as that along the orbital motion of Neptune and brought *Voyager 2* closer to Neptune at the rate of 1.45 million km per day.

The next important step was the selection of the aiming point, i.e. where exactly in space and time *Voyager 2* would come closest to Neptune. The selection[2] of the aiming point was dictated on one side by a variety of science objectives and on the other by the need to avoid endangering the vulnerable spacecraft to hazards of the Neptunian system environment, such as ring-arcs, atmosphere and radiation belts. The science objectives included

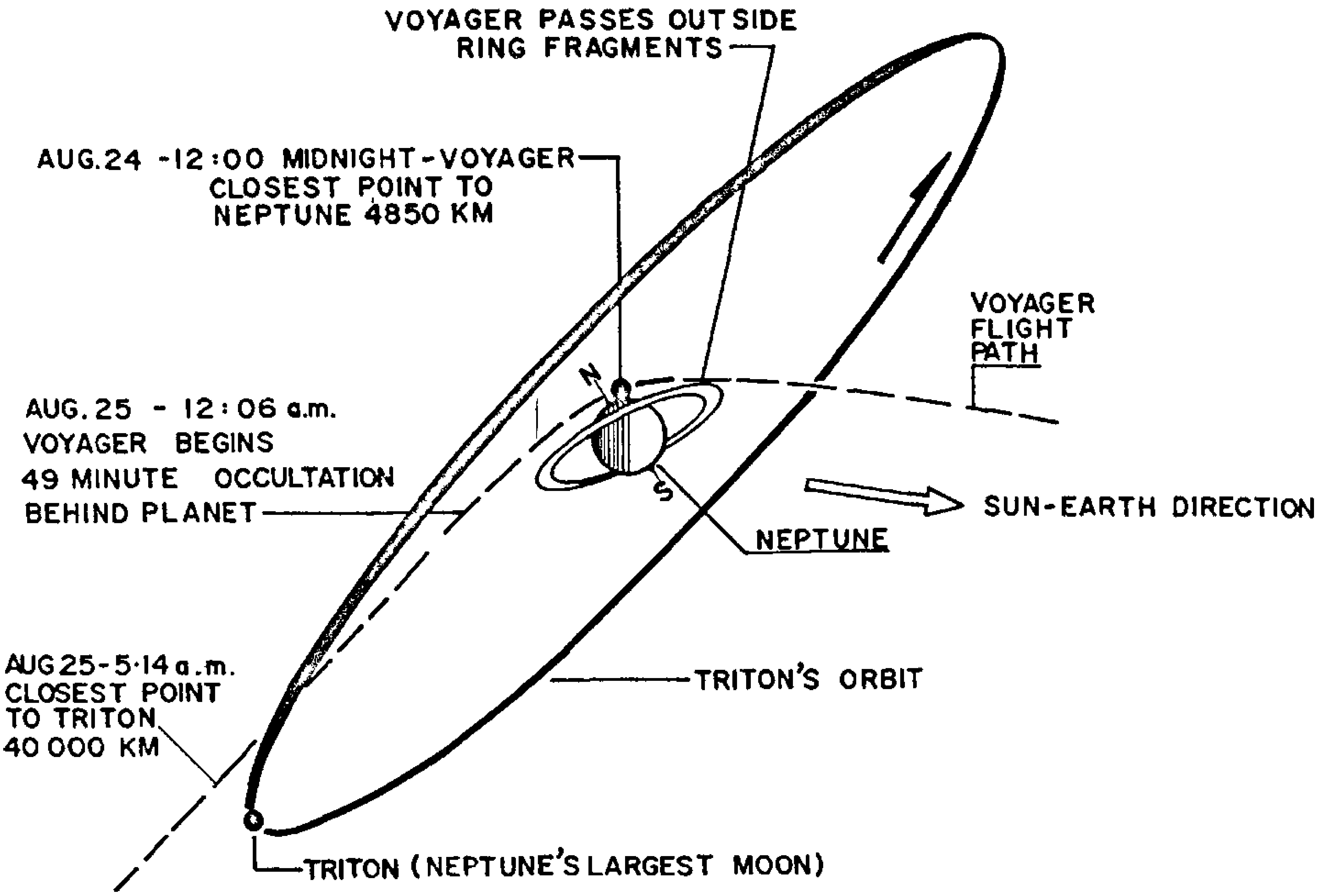

Figure 3. Geometry of the Neptune and Triton encounter, with time in EDT.

a close look at Triton and a detailed study of Neptune, penetrating into its magnetosphere as well as passing behind the planet to ensure that the spacecraft sensors and the deep space network (DSN) antennas on Earth could take advantage of the high-value Earth and Sun occultation conditions such a trajectory could produce. Occultation by Triton was another interesting possibility to be kept in mind. Multiple views of the purported ring-arc system were also considered desirable. Selection of the aiming point was dictated by these considerations and set up the geometry and timing for all encounter events, thus controlling most of the science-related parameters. The aiming point selection for Neptune was one of the most challenging of all the *Voyager* encounters, including those for *Voyager 1*. The various considerations led to the selection of the northern polar region near the 'inner Triton locus' as the most desirable place by which to make a fly-past of Neptune. This required a close pass over the northern polar region of Neptune to gain sufficient gravitational deflection for a close encounter with Triton five hours later (see figure 2). Refinement of these calculations, taking due account of the environmental hazards posed by the ring-arc system, enabled fixing the exact aiming point. The selected aiming point enabled *Voyager 2* to skim Neptune's northern polar region 4850 km from the cloud-tops (at 04:00 UT on August 25) and make the closest approach to Triton at 40,000 km. The actual point of closest approach was only about 30 km away from the predicted position and the spacecraft arrived at this point only 4 min earlier than the time predicted a decade ago! The early arrival was no reflection on *Voyager's* performance, but rather on astronomy's uncertain knowledge of Neptune's exact position in the solar system. Since its orbital period is 165 years and since it was discovered only 144 years ago, astronomers have not earlier observed Neptune at this point in its orbit.

SCIENCE HIGHLIGHTS

The atmosphere

The weather systems on Neptune imaged by

Voyager 2 were truly remarkable. With only ~5% as much heat to generate winds as on Jupiter (including the internal heat source and the small energy absorbed from the Sun), the surprisingly dynamic atmosphere of Neptune, with its storms and strong retrograde winds of over 1100 km/h, will require for its understanding complex mathematical modelling and detailed knowledge of the various physical processes responsible for the phenomena. A new feature observed as the spacecraft approached Neptune was the Great Dark Spot, located about 20°–22° south latitude, with dimensions as large as Earth's. It is reminiscent of the Great Red Spot on Jupiter, also located ~20°–22° south latitude. Both appear to be resulting from large anticyclonic storms in their atmospheres. The ratios of the sizes of the Great Spots to those of the respective parent planets are strikingly equal. *Voyager 2* also observed high cirrus clouds that change rapidly and cast shadows on a deeper cloud layer some 50–75 km below.

Rings

Prior to the *Voyager* mission, ground-based observations of stellar occultations by Neptune had already given evidence for the existence of three narrow ring-arcs around the planet. Several models had been advanced to explain the ring-arcs. One of them required shepherding moons with orbits inclined to the plane of the ring-arcs. *Voyager 2* discovered that the ring-arcs are nothing but parts of complete but tenuous rings. *Voyager 2* in fact discovered three complete rings and a broad sheet of ring material. Shepherding moons which constrain the ring boundaries were however not detected. The non-uniform distribution in azimuth of the ring materials still remains a puzzle to be solved.

Magnetic field

The magnetometers on *Voyager* detected a modest magnetic field on Neptune, ~0.4 gauss, not much stronger than Earth's field. But the surprising thing was that the axis of the dipole field was tilted about 50° with respect to the rotation axis of the planet and the effective dipole centre was found to have a large offset from the centre of the planet. Similar tilt was also observed on Uranus, but then it was thought that since Uranus itself was tipped on its side, such a tilt need not be considered too surprising. Now, Neptune is certainly not tipped like Uranus, and the tilt of its magnetic axis is therefore due to other causes, including the location of the dynamo-current system, which produce the field, perhaps being closer to the surface of the planet. The trapped radiation belt of particles, although weak, powers the aurora observed on Neptune's largest moon *Triton*.

Moons

Prior to the *Voyager* mission, there were only two moons known to be associated with Neptune, viz. Triton and Nereid. *Voyager 2* discovered six new moons, all of them dark, all of them orbiting prograde and, surprisingly, even the largest of them—1989 N1, with a radius of ~200 km slightly larger than Nereid, whose radius is only 170 km—irregularly shaped and showing little geologic modification. Moon 1989 N1 escaped detection with ground-based telescopes because of its proximity to the relatively brighter Neptune.

Triton

Triton, the largest moon of Neptune, is roughly the size of Earth's Moon. Its radius is about 1360 km. It is the only large moon in the solar system with a retrograde orbit. Its average distance from Neptune is nearly the same as the Earth–Moon distance. The orbital and rotational periods of Triton are the same, viz. 5.88 days, which implies that Triton shows the same face to Neptune, as does our Moon to Earth. *Voyager 2* discovered a thin atmosphere of methane and nitrogen on Triton. The surface pressure is only about 10 microbars. *Voyager* images also revealed the mottled appearance of the surface of Triton, with a variety of geological features, including possibly liquid nitrogen-spewing volcanoes that were active in the recent past. Triton also revealed an aurora, which implies the presence of a magnetic field and possibly a liquid core. With a surface temperature of only 37 K, Triton is so far the coldest object seen up close in the solar system.

TOWARDS MORE DISTANT ENCOUNTERS

Scarred by the violent radiation of Jupiter and the dust belt of Neptune and with its trajectory swung south of the ecliptic plane at an angle of 48° after the Neptune–Triton encounter, *Voyager 2* is heading on a new mission—a hunt for the edge of the Sun's influence and the shores of the great stellar ocean. Speeding away from the solar system at a rate of 60,000 km/h, and with the nuclear batteries capable of ensuring the operation of *Voyager 2* at least for another 25 years, the spacecraft could continue to explore the regions of space as far as 130 AU from the Sun. Scientists believe that it is travelling towards the leading edge of the magnetic bubble which represents the farthest reach of the Sun's magnetic field. A stream of protons, electrons and, to a lesser extent, helium nuclei, called solar wind, flows steadily outward from the Sun at velocities of the order of 400 km/sec. The region where the supersonic solar wind suddenly goes subsonic and where the influence of the Sun's magnetic fields ends is called heliopause. No one knows exactly where the solar system ends and interstellar space begins. Nevertheless, the heliospheric boundary is believed to be somewhere between 50 and 150 AU from the Sun. Mission planners estimate that *Voyager 2* will probably cross the heliopause around the year 2012 and enter true interstellar space. The first direct measurements of the environment outside our solar system, including interstellar magnetic fields and charged particles, will be hopefully possible at this time.

Beyond the heliopause, riding on its momentum, *Voyager 2* will continue its silent journey through the Milky Way, eventually passing within 4.03 light years of Bernard's star in the year 8571 and by Proxima Centauri in another 11,500 years. In the year 26262, *Voyager 2* should enter the Oort cloud, a region of comets orbiting the Sun. Travelling further, *Voyager 2* should pass within 4.3 light years of Sirius, the 'Dog star', in the year 296036. By that time, the wandering spacecraft will be 14.64 light years from home! According to the *Voyager* navigator, Tony Taylor, 'There is something wonderful about having a piece of humanity wandering among the stars; it is like having immortal children.'

Voyager 2, by sending down breathtaking views of other worlds, has created a growing awareness in us of Earth as a planet, and a very fragile one. The legacy of *Voyager 2* can be best expressed through the words of the poet T. S. Eliot: 'We shall not cease from exploration and the end of all our exploring will be to arrive where we started and know the place for the first time.'

ACKNOWLEDGEMENTS

The authors thank Prof. S. Ramaseshan, Distinguished Professor-Emeritus at the Raman Research Institute, Bangalore, for providing the encouragement to undertake this review of the *Voyager 2* encounter with Neptune for *Current Science*. Mr Arun Batra, Officer-in-Charge of ISRO Technical Liaison Unit at Washington, responded promptly to our request to collect the latest information on this encounter. He sent us considerable background material in the form of transcripts of NASA press briefings, technical notes and reports. Financial support for this work came from the Department of Space, Government of India.

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