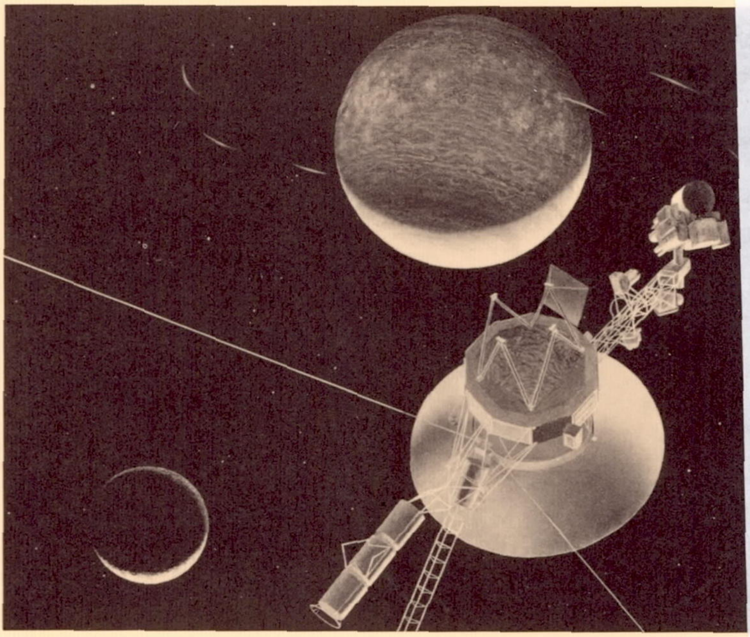
JPL Publication 89-24

The Voyager Neptune Travel Guide



June 1, 1989

NASA
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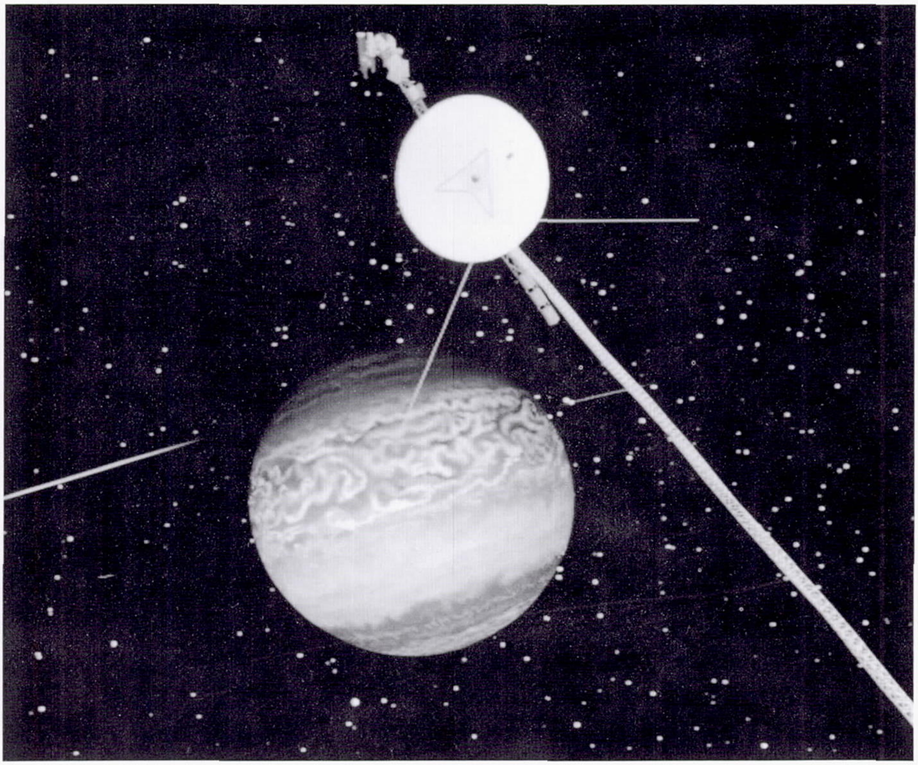

Voyager 2 approaches the sunlit hemisphere of the gas giant Neptune. In this computer-simulated view, one hour before closest approach on the evening of August 24 (PDT), 1989, we can see Neptune's ring arcs, believed to exist as a result of ground-observed stellar occultations. Just off the southern limb of Neptune (at about 7 o'clock), somewhat larger than the nearby star dots, we see the enigmatic moon Triton, which Voyager 2 will dive past six hours from now.

Cover: Looking back at Voyager 2 and the Neptune system two hours after Triton closest approach. *(Painting by artist Don Davis.)*

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Voyager Mission Planning Office Staff

Charles Kohlhase
Editor

June 1, 1989

NASA
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Voyager Neptune Travel Guide

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Abstract

This publication describes, in simple language and with numerous illustrations, the epic Voyager mission to explore the giant outer planets of our solar system. Scientific highlights include interplanetary cruise, Jupiter, Saturn, Uranus, and their vast satellite and ring systems. Detailed plans are provided for the August 1989 Neptune encounter and subsequent interstellar journey to reach the heliopause. As background, the elements of an unmanned space mission are explained, with emphasis on the capabilities of the spacecraft and the scientific sensors.

Other topics include the Voyager Grand Tour trajectory design, deep-space navigation, and gravity-assist concepts. The Neptune flyby is animated through the use of computer-generated, *flip-page* movie frames that appear in the corners of the publication. Useful historical information is also presented, including remarkable or *gee-whiz* facts associated with the Voyager mission. Finally, short summaries are provided to describe the major objectives and schedules for several exciting space missions planned for the remainder of the 20th century.

Let your soul stand cool and composed before a million universes.

Walt Whitman

1. INTRODUCTION

Congratulations! You are now the proud owner of a Voyager Neptune Travel Guide, hereinafter simply called the Guide. Its purpose is to explain **in simple language**, and with numerous illustrations, the Voyager-2 plans to examine Neptune and its moons, possible ring arcs, particles, and fields. A major attraction will be Neptune's large and unusual moon Triton. The Guide will also contain a variety of interesting facts about the Voyager mission, both past and future.

Before jumping into the particulars of the Neptune mission, let's briefly review the basic elements of an unmanned space mission. These elements are shown in Figure 1-1. You must, of course, have a **Spacecraft** capable of carrying a variety of sensors to the destination in order to conduct the **Science** you have in mind. The spacecraft cannot escape from Earth's gravity well without the help of a **Launch Vehicle**, either an expendable set of rocket stages or a reusable Space Transportation System, or Shuttle, with a high-energy upper stage.

No launch vehicle or spacecraft has an error-free guidance system, and so the process of **Navigation** is necessary to deliver the spacecraft to a precise location at the destination. As shown in Figure 1-2, the navigation process uses range (distance) and doppler (range rate) measurements from huge tracking antennas to estimate the spacecraft location to an accuracy of 1000 to 3000 km (620 to 1860 mi). As the spacecraft nears the destination, it takes pictures of natural satellites against a star background (a technique called optical navigation) to estimate its position to within 100 km (62 mi). If the spacecraft's flight path is off course, mission controllers send commands that cause the spacecraft to use small thrusters to correct its course.

As you have guessed by now, Voyager needs a lot of support from **Earth Base**. Voyager can cruise happily along, locked onto the Sun and a guide star, even using onboard fault protection logic to react to problems, but it still needs to hear from Earth regarding its activity plan.

A group of scientists decide upon an observation they would like Voyager to make. Flight team personnel from areas such as mission planning, science support, spacecraft engineering, flight operations, and sequence implementation, schedule and design the observation into a

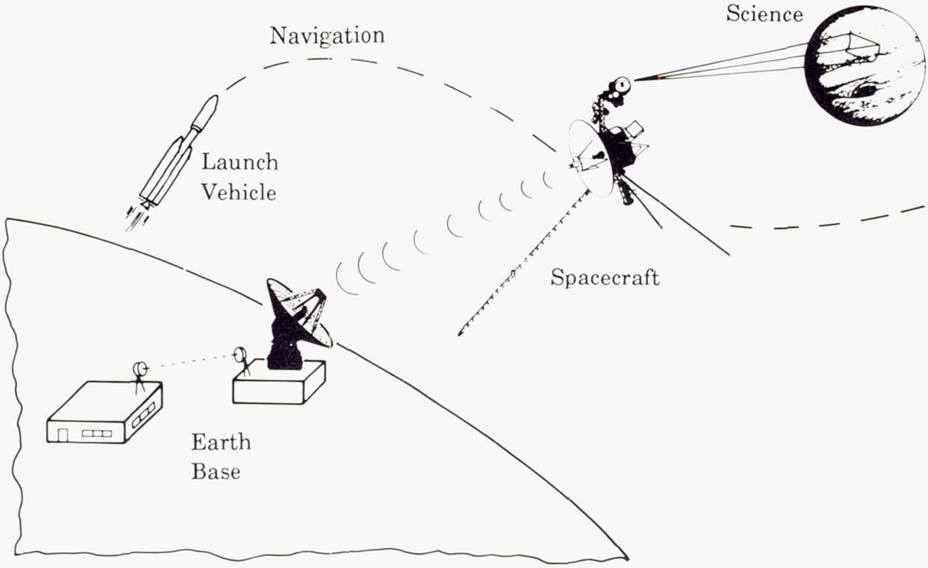


Figure 1-1. These are the five basic elements of an unmanned space mission. Earth Base is composed of a large complex of people, computers, communication lines, and tracking antennas. A manned space mission has a sixth element, the human crew for whom life support systems are required.

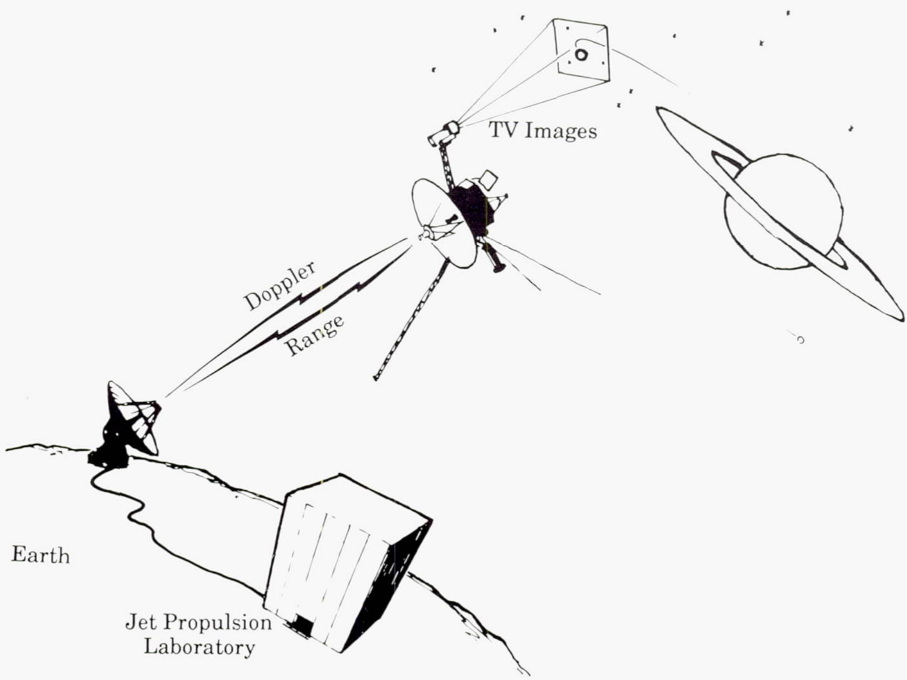


Figure 1-2. Navigators from Earth Base use radio tracking data and satellite-star images to estimate Voyager's position and heading.

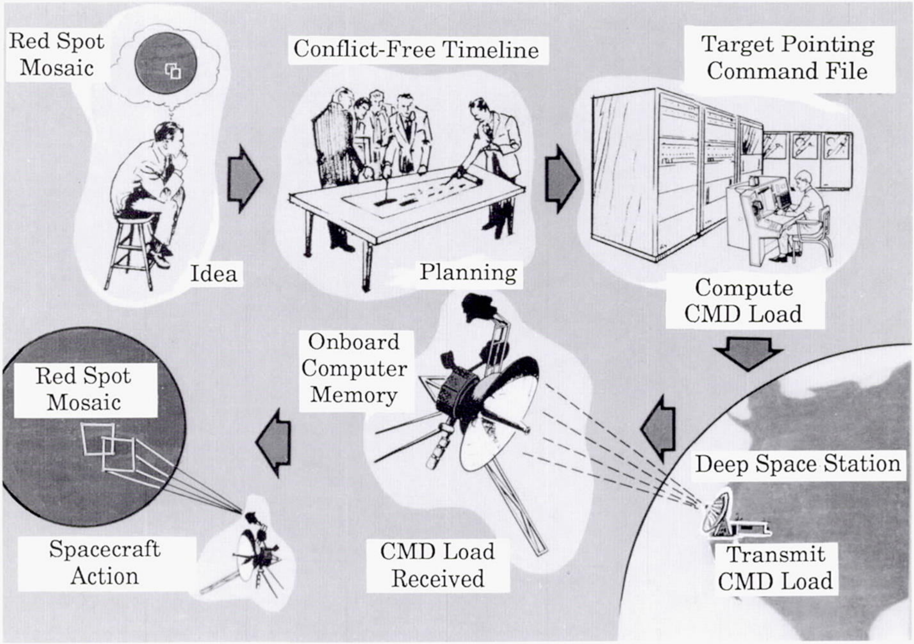


Figure 1-3. Many steps are necessary to develop activity sequences that Voyager will eventually execute.

master activity timeline. As shown in Figure 1-3, several steps are taken before Voyager finally carries out these instructions from Earth. Since Voyager has its own internal clock, desired activities can be loaded into its computers many days before they are to be executed. Each set of activities is termed a command load.

Voyager's Past

The Voyager mission has had quite a past. As shown in Figure 1-4, the two spacefaring robots were launched from Earth in 1977, bound for the giant planets of the outer solar system. These amazing machines are like distant extensions of the human sensory organs, having already exposed the once-secret lives of some four dozen worlds. Like remote tourists in never-never land, they have snapped pictures to reveal Saturn's dazzling necklace of 10,000 strands. Millions of ice particles and car-sized bergs race along each of the million-kilometer-long strands, with the traffic flow orchestrated by the combined gravitational tugs of Saturn, a retinue of moons and moonlets, and even the mutual interactions among neighboring ring particles.

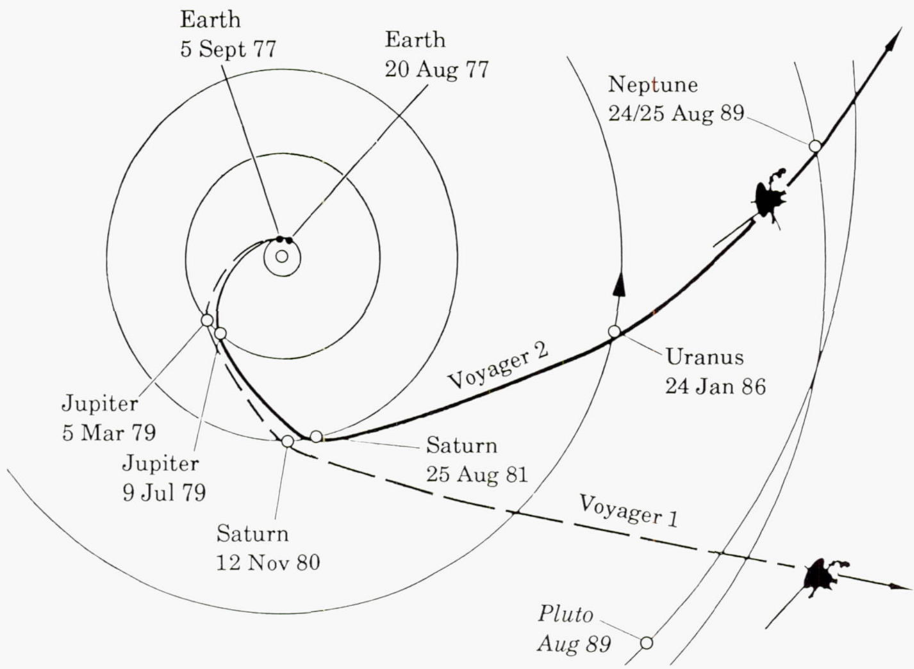


Figure 1-4. Though not discernible in this view, Voyager 1 was deflected upwards by its pass beneath Saturn. Voyager 2 remains near the ecliptic plane until its dive over Neptune deflects its path sharply downward, below the ecliptic plane. Accelerated by gravity assist, both Voyagers will cross the orbits of the outermost known planets by the turn of the decade, racing onward to escape from the solar system.

The Voyagers have shown us the erupting volcanoes of golden Io, the colorful and dynamic atmosphere of gargantuan Jupiter and its centuries-old Great Red Spot, the smooth water-ice surface of Europa that may hide an underground ocean, the strange world of Titan with its dense atmosphere and variety of hydrocarbons that slowly fall upon strange seas of ethane and methane, the small moon Mimas that was nearly destroyed by an ancient collision, the remote realm of tilted Uranus and its remarkable moon Miranda, and the many other wonders that have expanded the dimensions of our knowledge.

Anticipating Neptune

Can Neptune, discovered in 1846 at the Berlin Observatory (using mathematical predictions), possibly provide a level of excitement and wealth of new discoveries even close to those of the Jupiter, Saturn, and Uranus encounters? At first, the aquamarine gas giant Neptune appears to be Uranus' fraternal twin . . . but size and color alone tell only part of the story. Though Neptune is much farther from the Sun than Uranus is, its overall temperature is roughly the same, suggesting to scientists that Neptune has an internal heat source of its own, perhaps similar to those of Jupiter and Saturn. Each of the four seasons lasts more than 40 years, a period comparable to that of a human's entire working career from graduation to retirement.

Neptune has two known moons. Nereid, only 800 km (500 mi) in diameter, orbits so far from its planetary overlord that nearly one Earth year must pass before it can complete one lap around Neptune. Triton, on the other hand, is roughly the size of Earth's moon and laps the planet every six days in a direction opposite to the planet's spin. Ground-based observations of Triton indicate that it may have a thin atmosphere covering an icy surface with shallow pools of nitrogen, possibly liquid, but more probably cold enough to be solid like vast slabs of glass. Though not a sure thing, scientists are betting that Voyager's cameras will be able to photograph Triton's surface . . . unlike the circumstances at Saturn's haze-enshrouded moon Titan.

Humans find planetary rings beautiful, as borne out by the public's awe during the three previous encounters with gas giants. As if to spice matters up a bit, ground-based stellar occultation measurements seem to be saying that Neptune also has rings . . . but only in the form of many short arcs that do not connect like a necklace. The Voyager scientists are very excited about such a possibility, and different theories are being passed about to explain such an unusual situation.

Aside from the above scientific tidbits, which will be explored more completely in the next chapter, there should be an air of drama during execution of the encounter sequences. Voyager's close dive over the northern polar region of Neptune will provide only slight clearance above the outermost ring-arc region and the detectable atmosphere, and the radiation effects from particles trapped by the magnetic field cannot be disregarded. The round-trip communication time will be 8.2 hours; we will be slewing the same scan platform that became stuck for a period following the Saturn encounter; we will be using an onboard computer to compress the number of picture bits sent back to Earth; and, we will be programming Voyager 2 to perform several maneuvers to allow the cameras to take sharper images. The navigation challenges will also be worrisome at such a great distance from home. The bottom line? There should be plenty of excitement, as well as a few surprises, during the upcoming encounter.

The keys to the mysterious kingdom of Neptune lie just within our reach as Voyager 2 draws closer. The purpose of this Guide is to tell a piece of that story, thereby kindling our human quest to understand worlds beyond Earth that comprise a small region of the larger cosmos.

Notice: The information in this Guide was accurate at the time of publication, but may change by small amounts as time passes. Of primary relevance are some of the Neptune system physical characteristics, a few observational designs, and certain precisely quoted miss distances and event times.

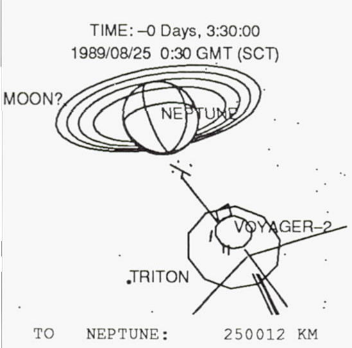
Lights, Camera, FLIP . . .

The flip-page movie in this Guide is your own animated memento of Voyager's historic swing past Neptune and Triton. The 133 frames cover a time period from 3.5 hours before to 7.5 hours after closest approach to Neptune. Watching the action through a 50° field of view, we pick up the spacecraft as it approaches the planet from slightly below the ring arcs, and ride along behind it as Voyager 2 sweeps up through the ring-arc plane, comes within 4850 km of Neptune's cloud deck, and then passes through Neptune's shadow. The suspected ring arcs are believed to move in the circular orbits shown outside of Neptune in its equatorial plane. According to some theories, a small 200-km-diameter moon (as yet undiscovered) orbits just beyond the orbit of the outermost ring arcs, determining the number of arcs in each of several interior orbits.

The gravity field of Neptune bends the flight path sharply south, below the ecliptic plane. Soon after closest approach to Neptune, we reduce our field of view to 20° as the spacecraft turns its attention to the moon Triton, and passes 40,000 km from Triton's center. The hatching next to the terminator denotes the body hemisphere in shadow. Its planetary encounters completed, Voyager 2 sails on towards interstellar space, leaving us with a parting glance back at the crescents of Neptune and Triton.

For your reference, the movie frames contain time and distance information. Both time from Neptune closest approach and "calendar time" are shown. The latter refers to GMT (Greenwich Mean Time) in SCT (spacecraft time). If you want PDT (Pacific Daylight Time), subtract seven hours. If you want ERT (Earth-received time), add 4 hours 6 minutes. The distance shown is measured from the viewer (near the spacecraft) to the center of either Neptune or Triton.

The wire-frame images were designed by the Voyager Mission Planning Office using the VAX-based SPACE software created by the JPL Computer Graphics Laboratory.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MOON?
NEPTUNE
VOYAGER–2
TRITON
TO NEPTUNE: 250012 KM

Astronomy compels the soul to look upwards and leads us from this world to another.

Plato

2. *NEPTUNE*

The final "stop" on our Grand Tour of the outer solar system is the planet Neptune. It is a stop in name only, for we do not really stop. In fact, as we get closer to Neptune, we speed up. It took twelve years to make the journey and we are very close to Neptune for but a few short days. During this period we will take the most detailed photographs of the planet and the only close photographs of its moons and possible ring system likely to be seen during our lifetimes.

A Glorious Construct Of The Mind

As you may recall, Sir William Herschel discovered Uranus from his backyard in 1781. Uranus was the first planet discovered since ancient times, causing great excitement in the world of astronomy. Anyone who could acquire the use of a telescope turned to observing the new planet. Scientists began cataloguing its position with time, to predict where it would be in the future. As the 18th century closed and the 19th century opened, astronomers began to have a small amount of trouble predicting the future location of Uranus. The planet simply did not appear in the part of the sky where it was supposed to be.

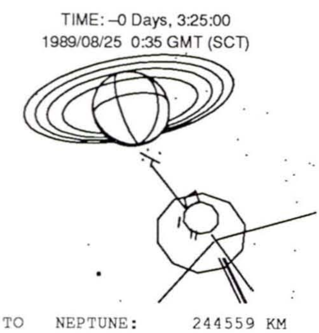
Isaac Newton's first law of motion states that once an object starts moving it keeps moving in exactly the same way unless a new force acts to change its motion. A fundamental law of matter (Isaac Newton's Law of Universal Gravitation) is that all bodies pull on each other. This pull is the only significant force that acts on planets as they orbit about the Sun. The largest pull is, of course, provided by the Sun itself. But each planet exerts a small pull on every other planet. All of these pulls must be taken into account when predicting the future location of any planet.

By the early 1800s, the difference between where Uranus was predicted to be, taking into account the other known planets, and where it actually appeared was getting to be quite noticeable. As early as 1824, Friedrich Wilhelm Bessel suggested that a new planet must be pulling on Uranus, causing the unpredicted motion.

At least two young mathematicians, working alone and unbeknown to each other, attempted to predict the size and location of the new planet that

Figure 2-1. Probably the first person to suggest that the irregularities in Uranus' orbit were caused by a new, more distant planet was the German mathematician Friedrich Wilhelm Bessel. *(A.H. Batten. Resolute and Undertaking Characters: The Lives of Wilhelm and Otto Struve. 1988. Permission granted by Kluwer Academic Publishers, Dordrecht, Holland.)*

must be pulling on Uranus. In England, John Couch Adams completed the calculations first, in 1845. He privately informed the English Astronomer Royal, George Airy, that if one was to look in a certain place at a certain time one would discover a new planet. Airy chose to disregard the prediction and did not make the observation. Subsequently, Airy did send Adams' calculations to James Challis, Plumian professor of astronomy and director of the Cambridge Observatory. Ironically, Challis recorded the new



planet twice without realizing his success. Along this vein, more than fifty years earlier, Joseph Lalande recorded the new planet twice over three nights . . . but attributed the slightly different positions of this find to observational error!

Meanwhile, in France, Urbain Jean Joseph Le Verrier completed his own calculations the following year. He turned his results over to both Airy and the French Academy of Sciences in published form, with a prediction on where and when to look to discover the new planet. His prediction was within one degree of Adams' earlier independent prediction.

The same fate befell his work as befell Adams' results: no observers used the predictions to look for a new planet. Finally, almost in desperation,

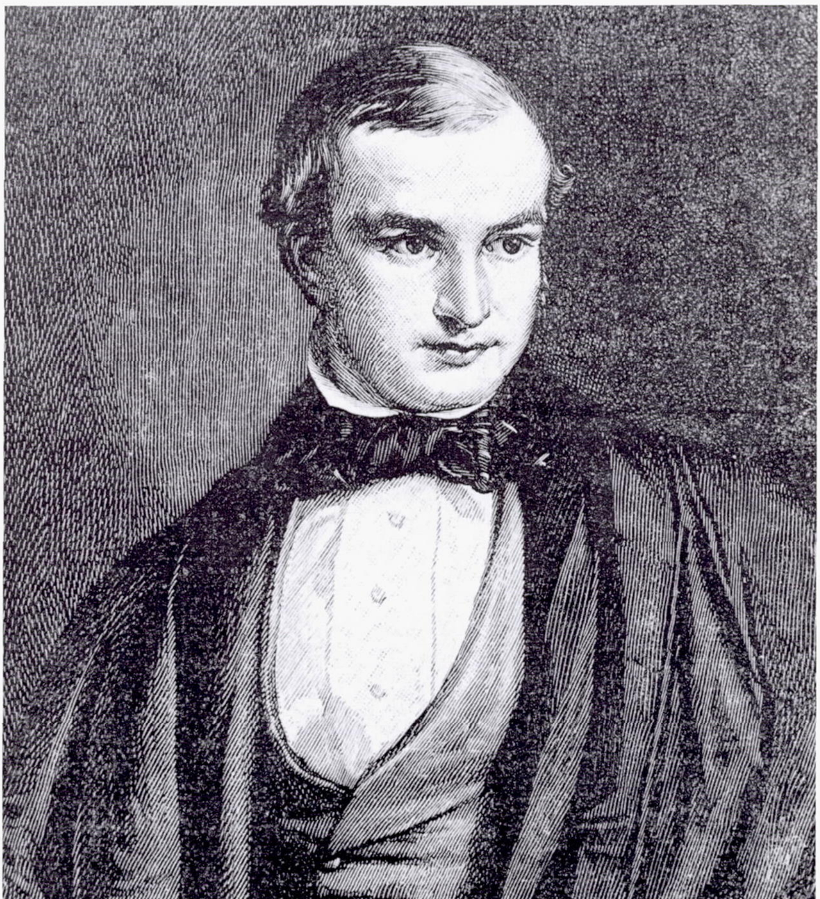
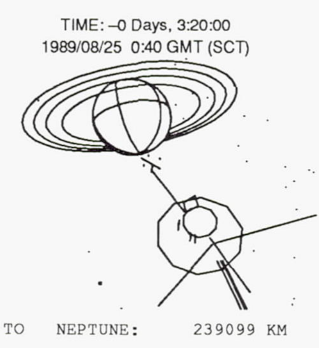


Figure 2-2. The first person to calculate the location of Neptune was the English mathematician John Couch Adams. Unfortunately, Adams did not publish his work right away, and the calculations of another were used to discover the new planet. *(Robert Ball. Great Astronomers. London, 1895.)*

Figure 2-3. ***The French mathematician Urbain Jean Joseph Le Verrier was the second person to determine the location of Neptune, but the first to publish his results. When no one would listen to his prediction, he mailed a request to a young astronomer at the Berlin Observatory, asking for a search.*** *(Illustrated London News, February 2, 1847.)*

Le Verrier sent his results to the unknown young German astronomer Johann Galle. The night of the day he received Le Verrier's prediction, September 23, 1846, Galle and a graduate assistant, Heinrich d'Arrest, with the aid of recently constructed star maps, sighted an unknown "star" in less than one hour and within one degree of where Le Verrier said Neptune would be. When, the following night, the new star exhibited a disk and had moved, the discovery was confirmed.



Perhaps the greatest intellectual accomplishment possible is to predict the existence of a phenomenon of nature *before* it is ever observed. Adams and Le Verrier independently accomplished this feat by correctly predicting the existence and location of Neptune before it had ever been observed.

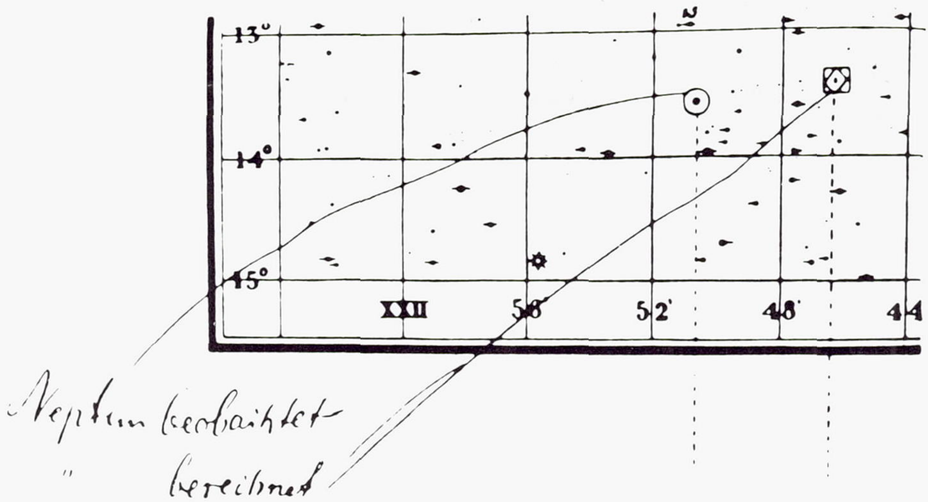


Figure 2-4. The night of the very day that Johann Galle received Le Verrier's request, he and a graduate assistant, Heinrich d'Arrest, sighted Neptune. This is a copy of the actual star chart used by Galle and d'Arrest to discover the new planet. The square is the position of Neptune predicted by Le Verrier. The circle is the position where Neptune was first observed. *(Hora XXI of Berlin Academy's Star Atlas, annotated by J.G. Galle. Courtesy Archenhold-Sternwarte, Berlin, East Germany.)*

What We Know

One hundred and forty-three years have elapsed since the first observation of Neptune. In that time we have acquired only the most basic knowledge about Neptune and its environs. We know how far it is from the Sun (30 astronomical units, or AU), its basic color (blue), size (57 times the volume of Earth), atmospheric composition (mostly hydrogen, helium, and methane), mass (17 times the Earth), effective temperature (about 60°C above absolute zero), the length of its year (165 years) and day (nearly 18 hours), and that it has at least two moons (Triton and Nereid). We know precious little else about the place.

Neptune is a gas giant, literally an immense ball of various gases that become denser as one goes deeper, with no solid surface as we know it. Jupiter, Saturn, and Uranus are all gas giants. When one looks at the photograph of a gas giant, one is looking at the top of the atmosphere and, when warm enough, the cloud tops just below. Uranus appeared bluish green in color.

Neptune is expected to look much the same way, and for exactly the same reason. The blue is produced by sunlight (of all colors) being robbed (absorbed) of its red and orange colors by methane. The remaining blues, and

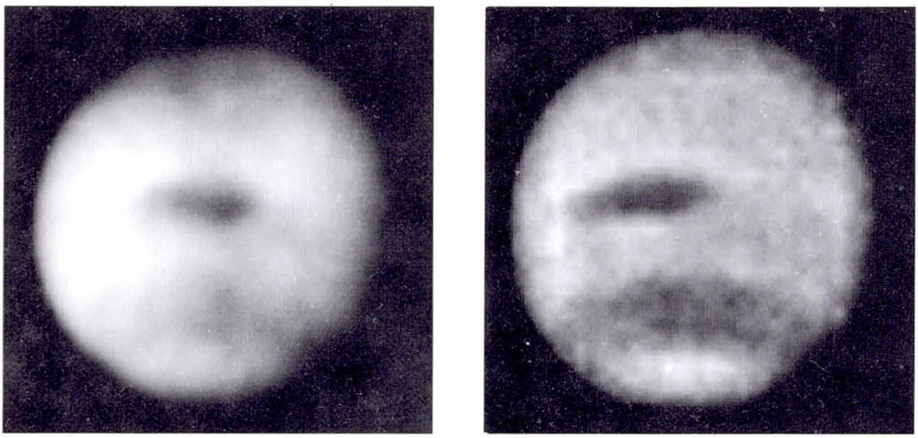


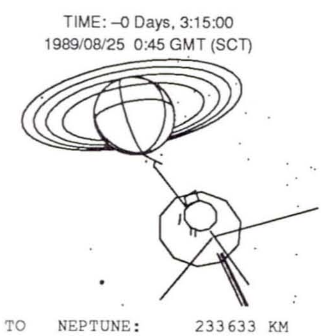
Figure 2-5. In these Voyager images taken in April and May 1989, Neptune shows cloud-type features much earlier than Uranus did. At a resolution nearly five times better than Earth-based, the hints of "gaseous topography" are tantalizing.

to a lesser extent greens, are reflected back to the viewer. Earth-based observations, as well as those by Voyager (see Figure 2-5), have indicated that Neptune has large cloud features.

Neptune's equator is tilted with respect to its orbit about the Sun by almost 29 degrees. This is slightly more than the 23.5 degrees of the Earth's tilt, and produces the same effect: seasons. Voyager 2 will arrive during winter in Neptune's northern hemisphere. Temperatures range from a minimum of about 50°C above absolute zero some 50 km above the cloud tops to several hundred degrees warmer as one goes deeper into the gases. Neptune gives off more than twice as much heat as it receives from the Sun.

Until 1988, we had no evidence that Neptune had a magnetic field. However, recent Earth-based observations have detected what may be synchrotron radiation near Neptune, an indication that this planet, too, has a magnetic field. Estimates of the surface field strength range from 1/2 to 1 gauss–about equal to or twice that of Earth's magnetic field strength at the surface.

English astronomer William Lassell first observed Neptune's large moon Triton a mere two-and-one-half weeks after Neptune itself was first observed. Unfortunately, a solar conjunction prevented the discovery from being confirmed until July 1847. Only one other Neptunian moon has been discovered to date. The small moon Nereid was first observed by American astronomer Gerard Kuiper in 1949, only forty years ago.



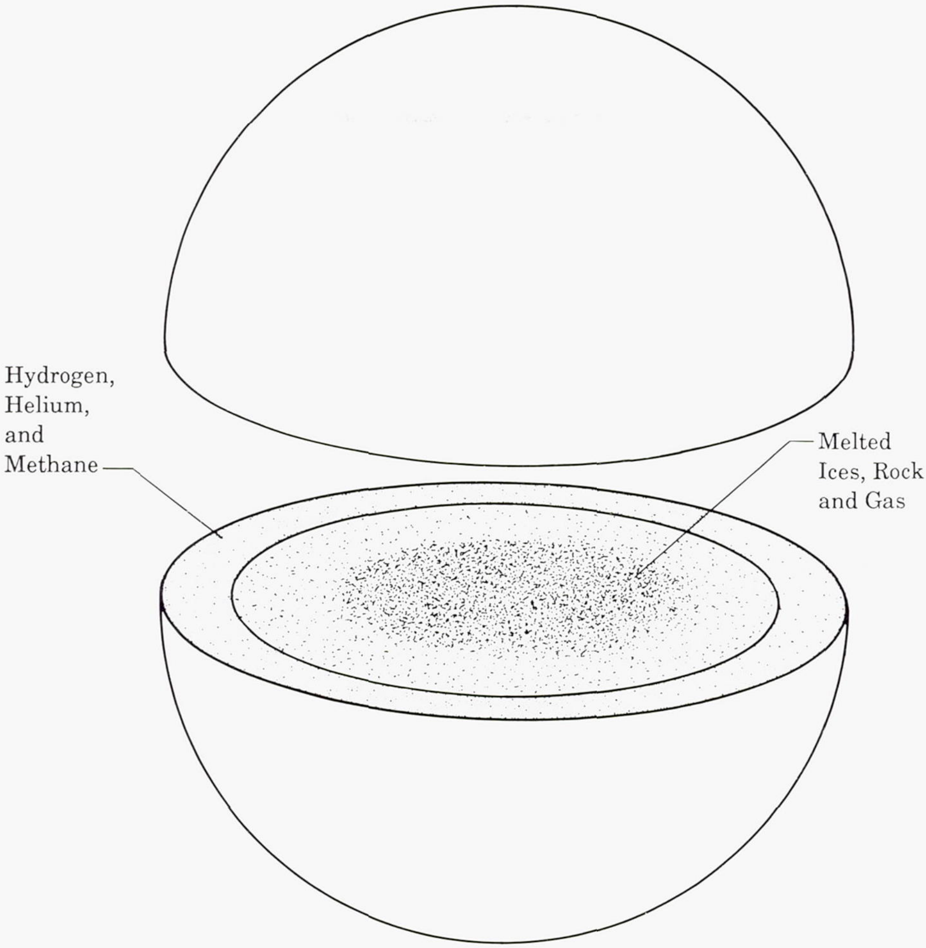


Figure 2-6. Neptune is really a very simple gas giant. It probably has a thin outer atmosphere of hydrogen, helium, and methane gases. The interior is probably a mixture of rocks, ices, and liquids, with more rock the closer one gets to the center.

Triton may very well prove to be one of the most interesting places in the solar system. It certainly has the credentials. The moon orbits Neptune in a retrograde or backwards direction, opposite to the planet's rotation on its own axis. Triton's orbit is also tilted with respect to Neptune's equator by some 20 degrees. Various scientists (Issei Yamamoto in 1934, Raymond Lyttleton in 1936, and Gerard Kuiper in 1956) have proposed that some cataclysmic event in the past flung Pluto into its own tilted orbit about the Sun, and wrenched Triton into its current backwards tilted orbit about Neptune. However, the discovery of Pluto's moon Charon has cast doubt on this hypothesis.

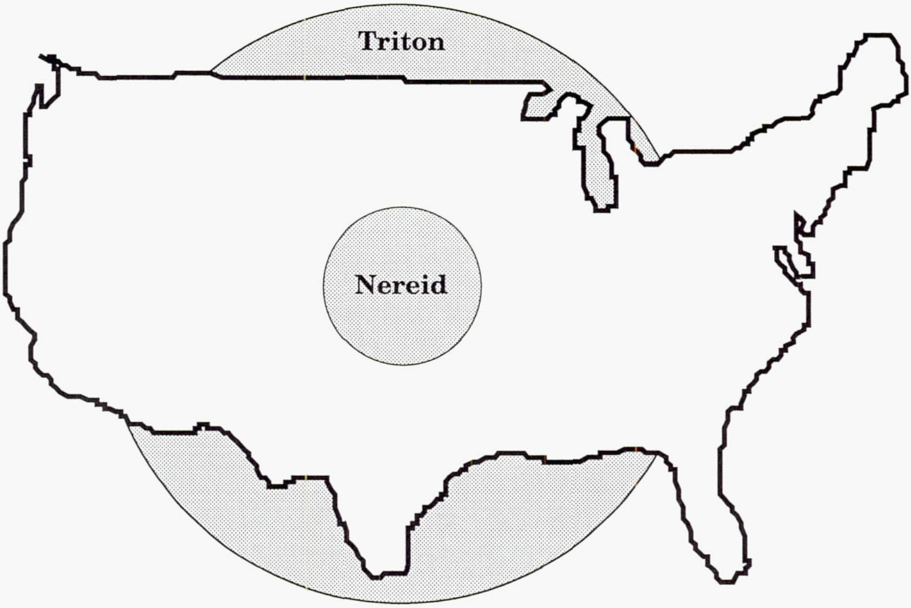
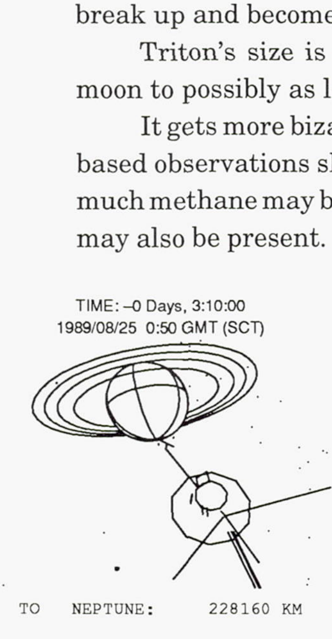


Figure 2-7. Neptune has two known moons: the largish Triton and the smallish Nereid. The Voyagers discovered three new moons each at Jupiter and at Saturn, and ten new moons at Uranus. Small moons about distant planets are hard to detect from Earth. Thus, the potential for Voyager 2 to discover new moons at Neptune is high.

Triton takes just under 6 days to complete one orbit, and this period is steadily (but very slowly) decreasing, as Triton spirals closer to Neptune as a result of tidal interactions. It has been estimated that within one hundred million to one billion years Triton will spiral in close enough to Neptune to break up and become a new set of rings.

Triton's size is quite uncertain, ranging from smaller than Earth's moon to possibly as large as the planet Mercury.

It gets more bizarre: Triton appears to have a thin atmosphere. Earth-based observations show absorption due to methane frost and/or gas. How much methane may be present is unknown, and other gases such as nitrogen may also be present. The surface temperature is near the triple point temperature of nitrogen. Earth-bound readers of this Guide will appreciate the significance of a triple point. Both the pressure and temperature of the surface of the Earth are near the triple point of water, allowing solid, liquid, and vaporous water to coexist. Although Triton's atmospheric pressure is expected to be well below nitrogen's triple point pressure, it is possible



that shallow pools of liquid nitrogen or, more probably, glaciers of frozen nitrogen may be present on Triton!

The state of knowledge about Nereid makes the state of knowledge about Triton look encyclopedic. Nereid is known to orbit about Neptune in a normal manner (i.e., in the same direction that the planet rotates on its own axis), albeit sixteen times farther away from Neptune than Triton is, and to take almost an Earth year to do it (see Figure 11-3). The uncertainty in Nereid's size is such that the best estimate recently increased by 60 percent! This moon is thought to be an ice ball, with perhaps some rocky material distributed throughout. Some astronomers report that Nereid's brightness has been observed to change by a factor of four over a period of 2-1/4 days. If true, such variations could be caused by apparent size or surface brightness changes as the satellite rotates.

All of the preceding is totally straightforward compared to the state of affairs on the Neptunian ring system. Until this decade there was absolutely no indication that Neptune had rings. In the past nine years astronomers have observed numerous stars as Neptune passed in front of (occulted) them. Out of one hundred and ten such occasions, eight times a mysterious event occurred. The starlight dimmed for a short period of time *either before or after the star was completely occulted by the planet.*

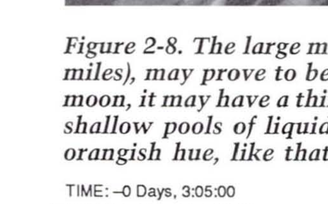
The dimming of starlight from an occultation usually indicates the presence of a ring system. However, whenever planetary rings have been detected by stellar occultations, the ring occultations always occurred symmetrically *both before and after* the planet occultation. So what are we to assume? Because the starlight only dimmed, but did not totally vanish, tenuous ring material is a more likely culprit than a solid moon.

In summary, only about seven percent of Neptune stellar occultations have produced "ring" occultations, and no "ring" occultation has been observed to occur both before and after the planetary occultation. The leading hypothesis to explain these bizarre events is that there is a set of at least three partially filled orbits of ring material (called ring arcs) encircling Neptune. About seven percent of the circumference of each ring-arc set is assumed to be filled with ice and rocks. It must be strongly emphasized that the "ring arc" explanation is the current best guess. There may well not be rings at Neptune.

Rewriting The Book

Voyager carries sensors for eleven scientific investigations. You will learn in depth about Voyager's sensors and investigations in Chapter 5. Suffice it to say that Voyager "rewrites the book" by observing, both from a

Figure 2-8. The large moon Triton, with an estimated diameter of 3000 km (1860 miles), may prove to be the show-stopper at Neptune. About the size of Earth's moon, it may have a thin atmosphere of methane and perhaps nitrogen, with very shallow pools of liquid or, more probably, frozen nitrogen on its surface. Its orangish hue, like that of Saturn's moon Titan, suggests that sunlight may be breaking down the methane and creating a variety of organic particles in the form of hydrocarbon-based aerosols. (Courtesy of the artist Ron Miller)



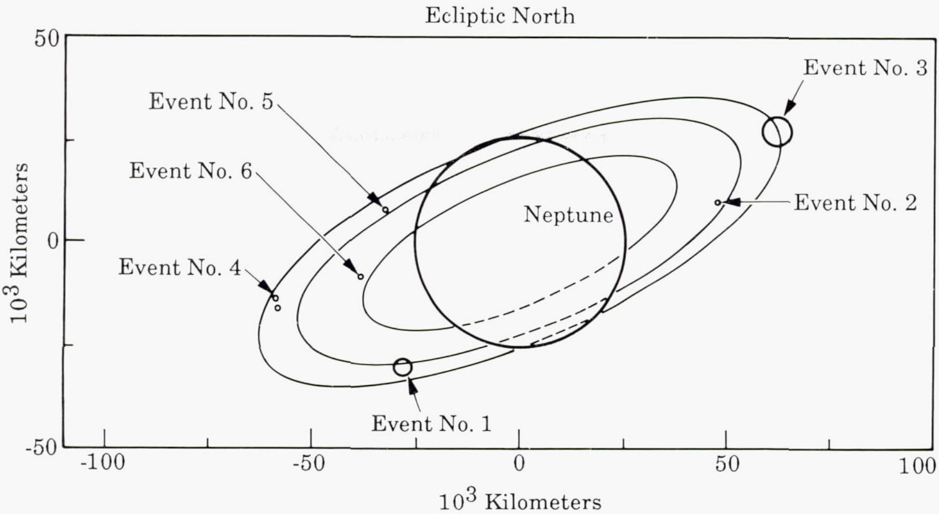


Figure 2-9. One hundred and ten attempts have been made to observe stars as they appear to pass behind Neptune. Eight times the starlight has dimmed, either before or after the star was occulted by the planet. The locations of the first six of these eight mysterious events are plotted in this plane-of-the-sky map of Neptune. The remaining two events are still being analyzed for precise locations. The current leading explanation involves three sets of incomplete rings, called ring arcs.

distance and up close. The closer the spacecraft gets to its target, in general the better all of its sensors work. Voyager will make its most important measurements when it is closest to Neptune, Triton, Nereid, and the hypothetical ring arcs.

For the Neptune Encounter, Voyager has three major scientific objectives: to help us learn as much as possible about Neptune, Triton, and Neptune's magnetic field. On a more detailed basis these general objectives expand to:

(a) Accurately determine Neptune's basic characteristics: color, cloud features, size, mass, density, composition, temperature, temperature variations, heat balance, wind speeds, and rotation rate.

(b) Determine Triton's basic characteristics: color, surface features, size, mass, density, composition, temperature, rotation rate, if there is an atmosphere and, if so, its temperature, pressure, and composition.

(c) Search for new moons, and characterize as many as possible.

(d) Search for rings (or ring arcs), and characterize as many as possible.

(e) Characterize Neptune's magnetic field strength, center location and orientation, and the structure and composition of any charged particles within the resulting magnetosphere.

(f) Search for other planetary phenomena, such as lightning, auroras ("Northern Lights"), and radio emissions.

(g) Accurately determine the Neptunian system's basic characteristics: position in time and rotational pole orientation.

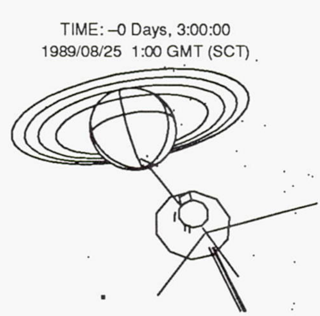
(h) Determine Nereid's basic characteristics: color, size, and shape.

Voyager is a robot, and must be told exactly what to do. Lists of such instructions are called software programs, or in Voyager parlance Computer Command Subsystem (CCS) loads. A CCS load consists of many subprograms called links. Each link contains the instructions to accomplish a specific science observation or engineering support goal. For example, the link that takes the highest resolution photographs of Nereid is called VNBEST.

The science links have a well-defined naming convention. The first letter designates the sensor (P = Photopolarimeter Subsystem, R = InfraRed Interferometer Spectrometer and Radiometer, U = Ultraviolet Spectrometer, V = Imaging Science Subsystem or TV, X = Radio Science Subsystem S/X-band, A = Planetary Radio Astronomy, W = Plasma Wave Subsystem, and F = Fields and Particles [Low-Energy Charged Particle, Cosmic Ray Subsystem, Plasma Subsystem, or Magnetometer]). First letters of link names can also refer to engineering or navigation activities.

The second letter in the link name designates the target body. (P = Planet [Neptune], T = Triton, N = Nereid, S = System, R = Ring arcs, H = Helios or Sun, X = unknown satellite, and C = Calibration or Configuration). The remaining letters and numbers in each link name provide a shorthand description of the observation. Chapter 6, Encounter Highlights, contains a summary of the times and goals of the most important science links.

So where do we stand in our knowledge about Neptune? We are not sure if it has rings. We have no idea if it has lightning. The colors and sizes of Triton and Nereid are not well known. It is thought that Triton has an atmosphere of methane and perhaps nitrogen, but we do not know its thickness or whether the surface can be seen. Will the surface, if seen, reveal shallow pools of frozen or liquid nitrogen? It must be kept in mind that Nereid and Triton have never appeared in any telescope as any more than pinpoints of light. Even Neptune has never appeared as more than a fuzzy ball. The answers to the above questions, and many more, will hopefully be revealed during the summer of 1989 as Voyager 2 provides our first close encounter with Neptune.



Man alone is the architect of his destiny.

William James

3. *GETTING THE JOB DONE*

When you are asked to think about space missions to the planets, you will probably think about stuff. Tangible stuff. You might think about the spacecraft, over 800 kilograms (nearly one ton) of structure and electronics gear. You might think of giant antennas to receive the signals from outer space. You might think of control centers with video displays and red, green, and yellow lights.

But you might not think of people, plans, and coordination. You should. This is the intangible stuff from which planetary missions are made. The theme of Voyager's people runs through this chapter of the Guide. Their performance through August 1989 will determine if Voyager Neptune earns a gold medal.

The gold medal, reminiscent of the XXIVth Olympiad held in Seoul in 1988, provides us a good comparison. The Voyager encounter with Neptune is an Olympian event, in terms of cost, complexity, number of people, and world-wide involvement.

Planning

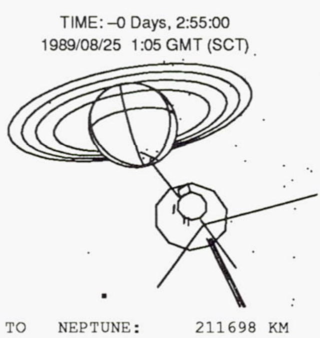
Start with the Voyager scientists. There are 130 Voyager investigators at universities, observatories, and aerospace companies scattered about the United States, Canada, England, France, West Germany, Italy, and the Soviet Union. The investigators are Voyager's competitors, by an elimination process at least as intense as the Olympic trials. They are supported by half again their number of research assistants and students. The investigators formulate the basic questions to be answered about Neptune, its satellites, and its neighborhood.

These questions require that Voyager 2 make specific observations at Neptune under just the right conditions. To match questions with observations requires a vast amount of information about the spacecraft and about Neptune. For example, just where is the spacecraft, and in what direction must the spacecraft look to see the various objects of interest? Determining the spacecraft position is the job of a 10-member group of spacecraft navigators at JPL who determine both the spacecraft location and the thruster firings needed to correct the location.

Figure 3-1. Charting Voyager's path through the solar system is a precise science, with only the occasional need to make artful choices among candidate "solutions."

Determining the locations of Triton and Nereid is initially the job of another 10-member group of orbit experts, some at JPL and some at places like the Universities of Texas and Virginia. They take the latest information available to refine the ephemeris (positions) of Neptune and its satellites. Remember, Neptune travels around the Sun so slowly that less than a Neptunian year has passed since its discovery, and less than three Neptunian months have passed since the discovery of its satellite Nereid by G. P. Kuiper in 1949. It's no wonder that there is still some uncertainty about precise locations, but these ephemeris experts can typically predict satellites positions to accuracies of 3000 km (1900 mi) or better many months in advance of the encounter. The predicted position of Nereid, however, has a much greater uncertainty.

The spacecraft navigators are after even better accuracies. They are equipped with some pretty fancy orbit determination computer programs that solve for the simultaneous positions of all bodies. Their most important data for updating the orbital elements of the satellites will be Voyager-2 images of the satellites against a known star background. By using the



narrow-angle TV camera to shoot satellite-star images until a few days before closest approach, these real-time navigators can estimate Triton's position relative to Neptune to 100 km (62 mi) or better. This is equivalent to locating the finish line for the marathon to an accuracy of 1/40 of an inch.

Okay, so we know where everything is. What's our master plan? We have limited resources and a rigid time schedule, but we want the greatest possible mission return. Voyager's Mission Planning Office (MPO) has the task of preparing a large collection of "guidelines and constraints" that govern how the Project resources and spacecraft consumables will be used to achieve high-value science return, while maintaining an acceptable level of risk. As suggested by Figure 3-2, the guidelines establish the envelope within which the mission sequences will be designed, implemented, and executed. The MPO function is analogous to that of the Olympic Organizing Committee. The time span is even comparable. Several of the basic decisions which were essential to the Neptune encounter were even made in the mid-1970s, well before launch.

Given knowledge of the satellite and target locations with time, scan platform pointing and observing conditions can be computed. The Science Investigation Support (SIS) Team at JPL, about 20 strong, acts as the focus

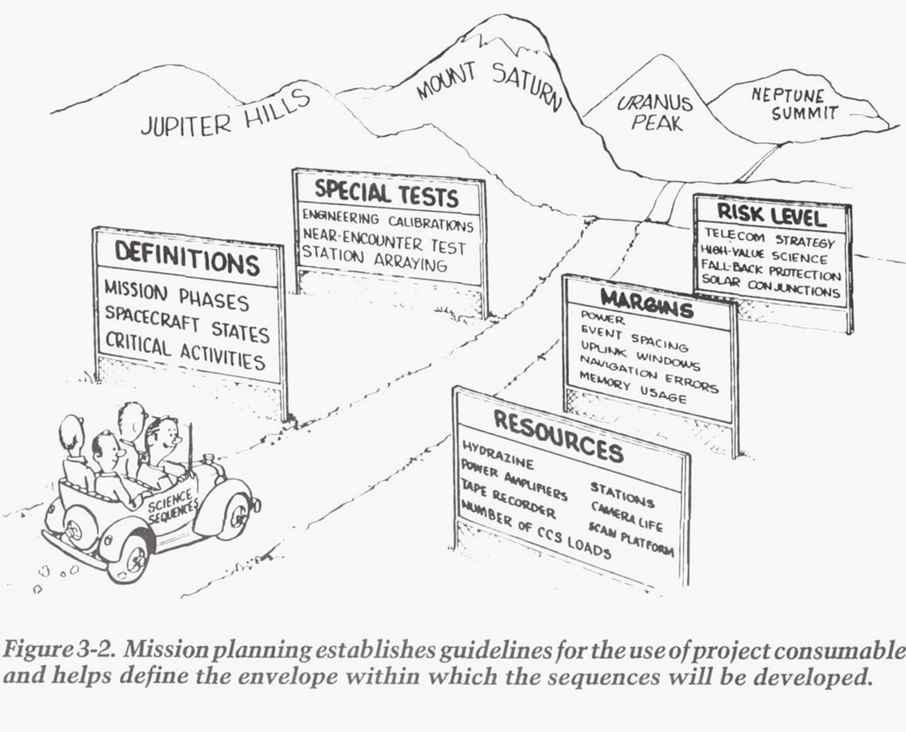


Figure 3-2. Mission planning establishes guidelines for the use of project consumables and helps define the envelope within which the sequences will be developed.

for the detailed science planning. Representatives for each experiment interact with investigators and other parts of the Voyager Project. The result is an integrated plan for all observations intended.

It is not uncommon for the investigators to desire conflicting observations. To resolve these conflicts, the Voyager Science Steering Group (SSG), composed of the Principal Investigators (the leaders of each of the eleven Voyager scientific teams), meets regularly at JPL to review the observation plans. The members of the SSG make the science decisions required to ensure that the observation plans will yield the best Neptune science.

Sequencing

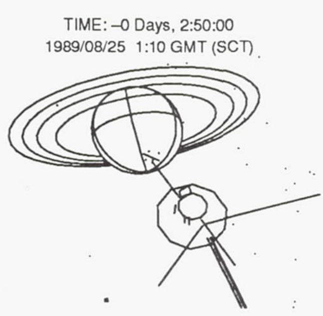
As soon as the final observation plan is ready, primary responsibility passes to the sequence development engineers. The Sequence Team consists of about 30 members at JPL who flesh out the observation plans with the instrument and spacecraft commands required to produce the desired results. The Sequence Team ensures that no operating constraints are violated and that all of the instructions to the spacecraft will fit into its computer memory. The Voyager-2 sequence computer, the Computer Command Subsystem (CCS), has roughly 2500 words of memory reserved for sequencing. Two words are required for a simple instruction: one to specify the event to take place, the other to specify the time of occurrence. For a period of high activity, such as Neptune near-encounter, CCS words are always at a premium.

The Spacecraft Team, about 70 engineers at JPL, is responsible for the health and optimal use of the spacecraft. It must analyze the spacecraft engineering telemetry to determine how the spacecraft is performing, as well as plan the engineering sequences that are needed for the observation plans to succeed. Roughly half the Spacecraft Team will be engaged in planning at any given time, while the rest will be involved with data analysis.

Engineering sequences, such as spacecraft maneuvers, are passed from the Spacecraft Team planners to the Sequence Team for incorporation into the CCS loads.

The total sequence design process from MPO guidelines through on-the-shelf CCS loads typically requires many months of technical interactions, give and take, teamwork, and decisions. Figure 3-3 is an early cartoon sketch of the process, but it is still close enough to today's perceptions to warrant inclusion in the Guide.

Once a CCS load has been built and verified, it is ready to be sent to the Voyager-2 spacecraft. The



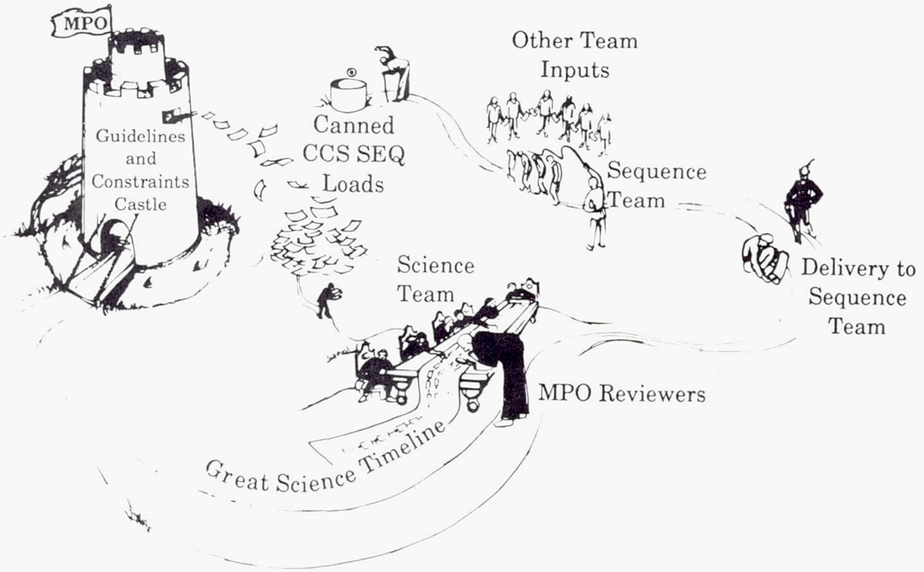


Figure 3-3. People often have humorous ways to view their working interrelationships, and Voyager is no exception (early version of "ye olde sequence design process").

final step by the Sequence Team is to process a CCS load from a text listing of commands to the stream of 1s and 0s (bits) which will actually be received by the spacecraft. Stored on magnetic computer tape, this binary command stream is passed to the Flight Operations Office (FOO).

Flight Operations

The FOO, comprising about 45 engineers located at JPL, is the real operator of the spacecraft. The FOO controls all transmissions to the spacecraft and receives all data at JPL from the spacecraft. It is responsible for coordinating the Voyager Project's activities with operational organizations outside the Voyager Project, such as NASA's Deep Space Network (DSN), JPL's Multimission Control and Computing Center (MCCC), and Goddard Space Flight Center's NASCOM communications network. Scheduling is one of FOO's most important activities. If a CCS load contains a critical observation of the Neptune atmosphere near encounter, the appropriate DSN ground antennas must be tracking Voyager 2 at that time, or the information returned from the spacecraft will fall on deaf ears.

During the Neptune encounter, the DSN will be tracking not only Voyagers 1 and 2, but also Pioneers 10, 11, and 12, and the Magellan probe to Venus. It may also be asked to track three earlier Pioneers (6, 7, and 8) and the International Comet Explorer (ICE). With such a demand for its services, the DSN scheduling process is involved, indeed.

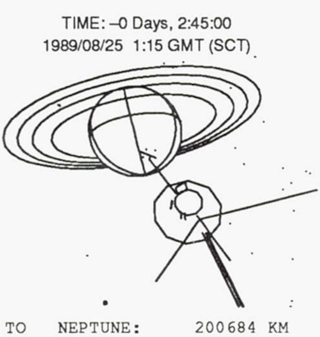
Representatives of the FOO meet with representatives of other projects far in advance of the requested coverage dates to hammer out an equitable allocation of DSN antenna support to all projects. Using MPO guidelines, the tracking schedule that results is used in the generation of observation plans by the Science Investigation Support Teams, the Navigation Team, the Spacecraft Team, and the Sequence Team. The amount of tracking that a spacecraft receives in any period depends on the relative importance of that period to its mission. Voyager 2 will receive the full resources of the DSN during its Neptune flyby, but will receive only sporadic tracking several weeks later as other spacecraft cry for increased tracking support.

Commanding

With the command tape prepared and the DSN and NASCOM scheduled, the CCS load can be transmitted, or uplinked, to Voyager 2. The tape will be played into the JPL-based Voyager Command System, where the command stream will be formatted to the Ground Communication Facility (GCF) standards, and sent via GCF to the appropriate DSN Deep Space Communications Complex (DSCC) for transmission to the spacecraft. GCF uses a combination of communication satellites and conventional surface and undersea circuits to link together JPL and the DSCCs, just as the TV networks did to broadcast the Seoul Games around the world. As the GCF message containing the command stream reaches the DSCC, it is checked for correct reception and the GCF formatting bits are removed. It is then routed to the transmitting station and sent to the spacecraft.

There are three DSCCs, located in California, Australia, and Spain. These locations were chosen at widely separated longitudes to provide essentially continuous tracking capability to any interplanetary spacecraft as the Earth rotates. The equipment at each site is similar.

The Goldstone DSCC is located near Goldstone Dry Lake in the heart of the Mojave Desert in California. Three antennas at Goldstone support the Voyagers: DSS 12, a 34-m (112-ft) diameter antenna which can both transmit and receive; DSS 14, a 70-m (230-ft) diameter antenna which can both transmit and receive; and DSS 15, a 34-m (112-ft) diameter antenna which can only receive. As shown in Figure 3-4, a 70-m antenna is quite a large structure. For increased performance, more than one antenna can be used simultaneously in array to increase the strength of the received signal



from Voyager 2 (see Chapter 9, Engineering Wizardry). The Goldstone DSCC is operated for NASA by JPL with a staff of 280 engineers and technicians. An additional cadre of managers, development engineers, and programmers for the DSN reside at JPL in Pasadena, California.

The Canberra DSCC is located in the semi-arid rolling hills of New South Wales at Tidbinbilla, not far from the Australian Capital Territory of Canberra. Three antennas at Canberra support Voyager 2: DSS 42, a 34-m (112-ft) transmit/receive station; DSS 43, a 70-m (230-ft) transmit/receive station; and DSS 45, a 34-m (112-ft) receive-only station. The Canberra DSCC is operated for NASA by 150 engineers and technicians from the Australian Department of Science.

The Madrid DSCC is located in the foothills at Robledo, Spain, near the capital city of Madrid. Three antennas at Madrid support Voyager 2: DSS 61, a 34-m (112-ft) transmit/receive antenna; DSS 65, a 34-m (112-ft) receive-only station; and DSS 63, a 70-m (230-ft) transmit/receive antenna. The Madrid DSCC is operated for NASA by the Spanish National Institute for Aerospace Techniques (INTA) with about 200 engineers and technicians (see Figure 3-5). Voice communications, basically a continuous phone call, are maintained between all three DSCCs and the Network Operations Control center at JPL.

One would surely think that we've got all the receiving antennas we could possible need. Not so, however. The Voyager signals are so feeble by the time they have crossed 4.5 billion km of space that we can make important use of even more giant ears to catch the Voyager news. Helping out Goldstone will be the twenty-seven 25-m (82-ft) antennas of the Very Large Array (VLA) (shown in Figure 9-1) near Socorro, New Mexico, operated by Associated Universities, Inc. as a part of the National Science Foundation's National Radio Astronomy Observatory (NRAO). Because the Neptune and Triton closest approach periods occur over the Australian longitude, helping out Canberra will be the 64-m Parkes Radio Observatory, located some 320 km (200 mi) northwest of the DSN complex. Parkes is operated by the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO). Finally, the 64-m radio observatory antenna at Usuda, Japan, will provide additional tracking during the critical radio science observations near closest approach. The Japanese Institute of Astronautical Science (ISAS) operates the Usuda antenna on the island on Honshu in the hills west of Tokyo.

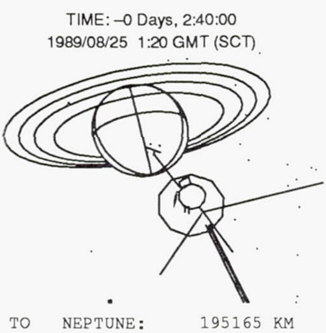
We left the command load just radiating from the DSS antenna on its way to Voyager 2. Even at the speed of light, the first command will not arrive at Voyager for 4.1 hours, and acknowledgement of its receipt can't be

Figure 3-4. If we could move the 70-m DSN tracking antenna from its Goldstone, California, desert location to the football field inside the Pasadena Rose Bowl, this is how large it would appear! Big ears are needed at Earth Base to hear the feeble signals from a remote spacecraft.

seen at Earth until 8.2 hours after it was sent. Data telemetered from Voyager 2 are 4.1 hours old the instant they are received. This time lag complicates operations greatly. Imagine driving a car where the gauge readings and even the sights seen out of the windows are over four hours old, and the response to turning the steering wheel or applying the brake is four hours in the future! Luckily, there is less traffic on the way to Neptune than there is on the Los Angeles freeways.

Receiving Data

The data received are of enormous value. First there is telemetry, which consists of information describing the performance of the spacecraft and its instruments and the science measurements themselves. The telemetry is identified with spacecraft time so that a complete reconstruction of the state of the spacecraft can be used to determine the health of all engineering and science subsystems, and to aid in science interpretation.



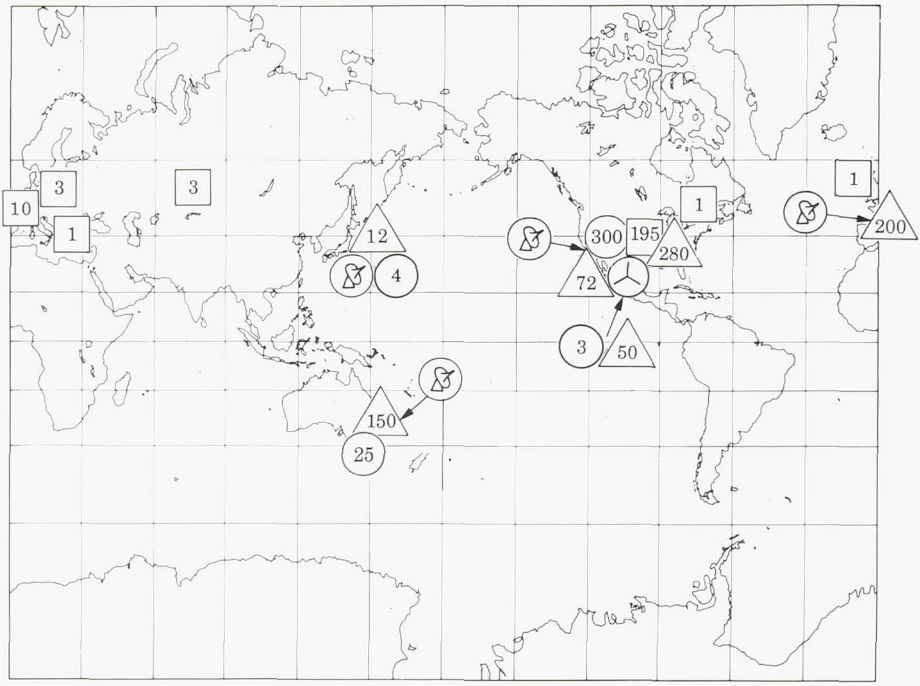


Figure 3-5. The Voyager family consists of full-time Voyager people (○), part-time Voyager people (□) and multimission support people (△). The tracking complex staffing levels shown represent the full complement of personnel who support not only Voyager, but several other missions as well.

Second there are navigation data. One type are doppler data, which are contained in the Voyager-2 radio signal itself and are dependent upon the relative motion between the spacecraft and tracking antenna. Another is range data, which provides a distance measurement from the spacecraft to the tracking antenna. A third uses simultaneous tracking by two stations of first the spacecraft and then a quasar of known characteristics to get a different type of doppler data. Finally, optical navigation video images relate the spacecraft and planetary body positions to their directions relative to known stars.

All of these data are both relayed (via GCF) to JPL and recorded at the DSCC. This allows any gaps to be recovered after the fact if any data are lost on the way to their ultimate user. The first users are the Mission Control Team, the Navigation Team, and the Spacecraft Team. Essential engineering measurements and status indicators are displayed as they are received so that corrective action may be initiated at any sign of a problem.

The entire data stream is routed through the Ground Data System (GDS), consisting of the DSN, NASCOM, MCCC and a number of Voyager

Project data systems. The data are finally processed by an assemblage of some 55 people and various computers at JPL. Here, the telemetry is read and identified, and reassembled by measurement rather than as a serial stream. If coding has been applied, it is decoded. Imaging is transferred to the Multimission Image Processing Subsystem (MIPS) to be converted from digital picture elements into pictures. If the imaging has been compressed (see Chapter 9), MIPS reverses the compression. During this process the images can be enhanced to bring out subtle features and, in some cases, even corrected for errors.

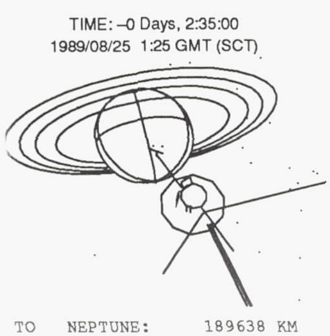
All imaging and non-imaging data are collected and processed into Experiment Data Records (EDRs), which contain all available science and engineering data from a given instrument. The EDRs are the basic delivery of observed data to the investigators. A companion record, the Supplementary Experiment Data Record (SEDR), contains the best estimate of the conditions under which the observations were taken.

If you would like to learn more about how we route the steady stream of data bits arriving at Earth from the Voyager transmissions, please refer to Figures 6-6 and 6-7, plus the accompanying text in Chapter 6.

The Results

As the encounter with Neptune approaches, delivery of the data to the investigators will become easier because the scientists will be migrating to JPL. As the pace quickens, monthly investigator meetings will become daily meetings, and ideas will be exchanged furiously as they strive to understand the details of a new planetary system. When the last of the Neptune data are safely acquired, the scientists will retreat with the data to their own institutions to begin the intensive process of converting measurements into answers to those fundamental questions raised in Chapter 2.

That won't be the end, however. Archived, the Voyager-2 Neptune data will be available to scientists the world over through the National Space Science Data Center at the NASA/Goddard Space Flight Center in Greenbelt, Maryland. It is a safe bet that somewhere today there are tens or hundreds of elementary school students who, in the early twenty-first century, will be writing doctoral dissertations based on their study of the Voyager-2 Neptune data. And that, in the year of the XXVIIth Olympiad, will be Voyager's real gold medal.



One wonders if their messages came long ago, hurtling into the swamp of the steaming coal forests, the bright projectile clambered over by hissing reptiles, and the delicate instruments running mindlessly down with no report.

Loren Eiseley

4. THE VOYAGER SPACECRAFT

The mission objectives can be met only by delivering the spacecraft to the Neptunian system along the chosen flight path, properly orienting the spacecraft and pointing its instruments at the desired celestial bodies, powering the instruments, giving instructions to them, and channeling the science information gathered to the radio subsystem for transmission to Earth. In other words, a pretty complex machine is necessary to support the science instruments. Several years before launch, a spacecraft design team (Figure 4-1) worked out the basic requirements for this amazing machine and, judging by its success to date, they did a first-class job.

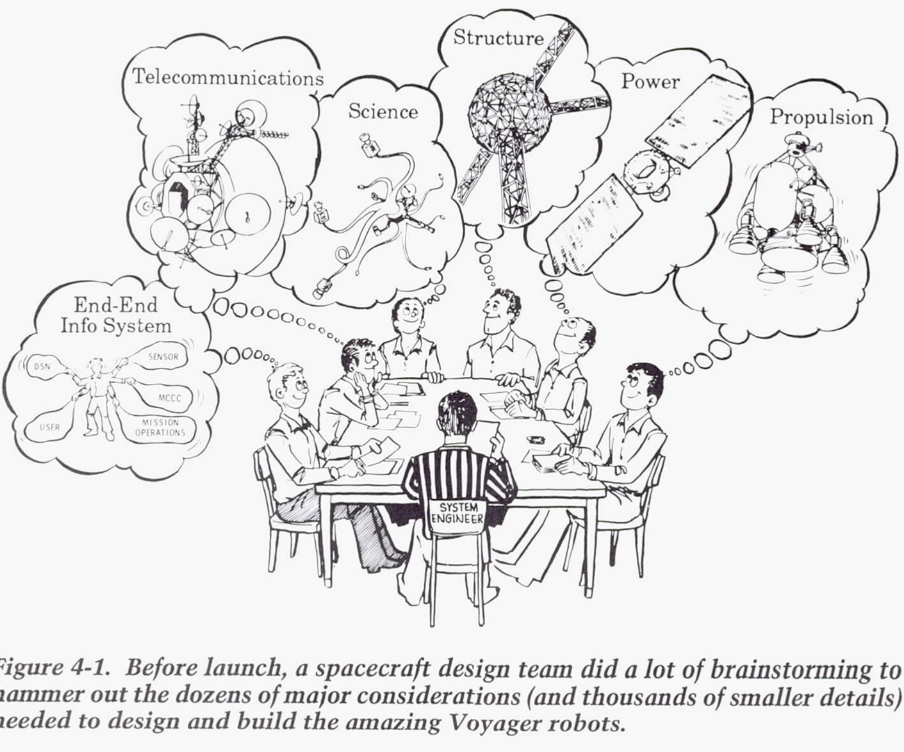


***Figure 4-1.** Before launch, a spacecraft design team did a lot of brainstorming to hammer out the dozens of major considerations (and thousands of smaller details) needed to design and build the amazing Voyager robots.*

Bus

The basic structure of the spacecraft is called the "bus," which carries the various engineering subsystems and scientific instruments. It is like a large ten-sided box, which can be seen in Figure 4-2. The centerline of the bus is called the z-axis, or roll axis. The spacecraft will usually be aligned so this z-axis (and thus the High Gain Antenna) points to Earth. The spacecraft is designed to roll about this axis by firing small thrusters which are attached to the bus. The thrusters are fueled by a liquid called hydrazine.

Each of the ten sides of the bus contains a compartment (a bay) that houses various electronic assemblies. Bay 1, for example, contains the radio transmitters. The bays are numbered from 1 to 10 (numbered clockwise as seen from Earth).

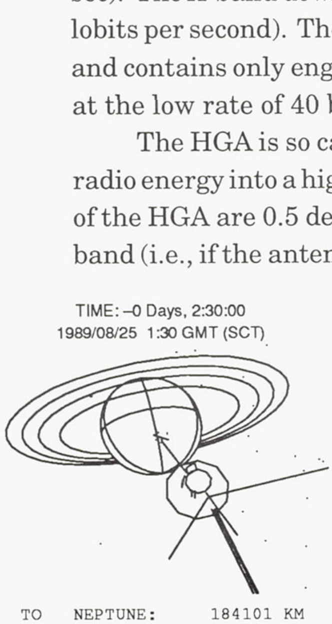
Two additional turn axes, at right angles to the roll axis and to each other, are needed to give the spacecraft full maneuverability. These are the x-axis (pitch) and the y-axis (yaw). The booms supporting the nuclear power sources and the scan platform lie along the y-axis.

High Gain Antenna (HGA)

On many spacecraft, a small antenna dish sits on the spacecraft bus and is steerable. But Voyager is different; it may almost be said that the spacecraft bus sits on the High Gain Antenna (see Figure 4-2.)

The HGA transmits data to Earth on two frequency channels (the downlink). One, at about 8.4 gigahertz (8,400,000,000 cycles/sec), is the X-band channel and contains science and engineering data. For comparison, the FM radio band is centered around 100 megahertz (100,000,000 cycles/sec). The X-band downlink science data rates vary from 4.8 to 21.6 Kbps (kilobits per second). The other channel, around 2.3 gigahertz, is in the S-band, and contains only engineering data on the health and state of the spacecraft at the low rate of 40 bps.

The HGA is so called because signal strength is gained by focusing the radio energy into a highly concentrated narrow beam. The half-power points of the HGA are 0.5 degrees off axis for the X-band and 2.3 degrees for the S-band (i.e., if the antenna strays as much as 0.5 degrees off point, the X-band signal strength drops by half). There is also a Low Gain Antenna, but it is not used anymore except in response to certain faults involving loss of spacecraft orientation.



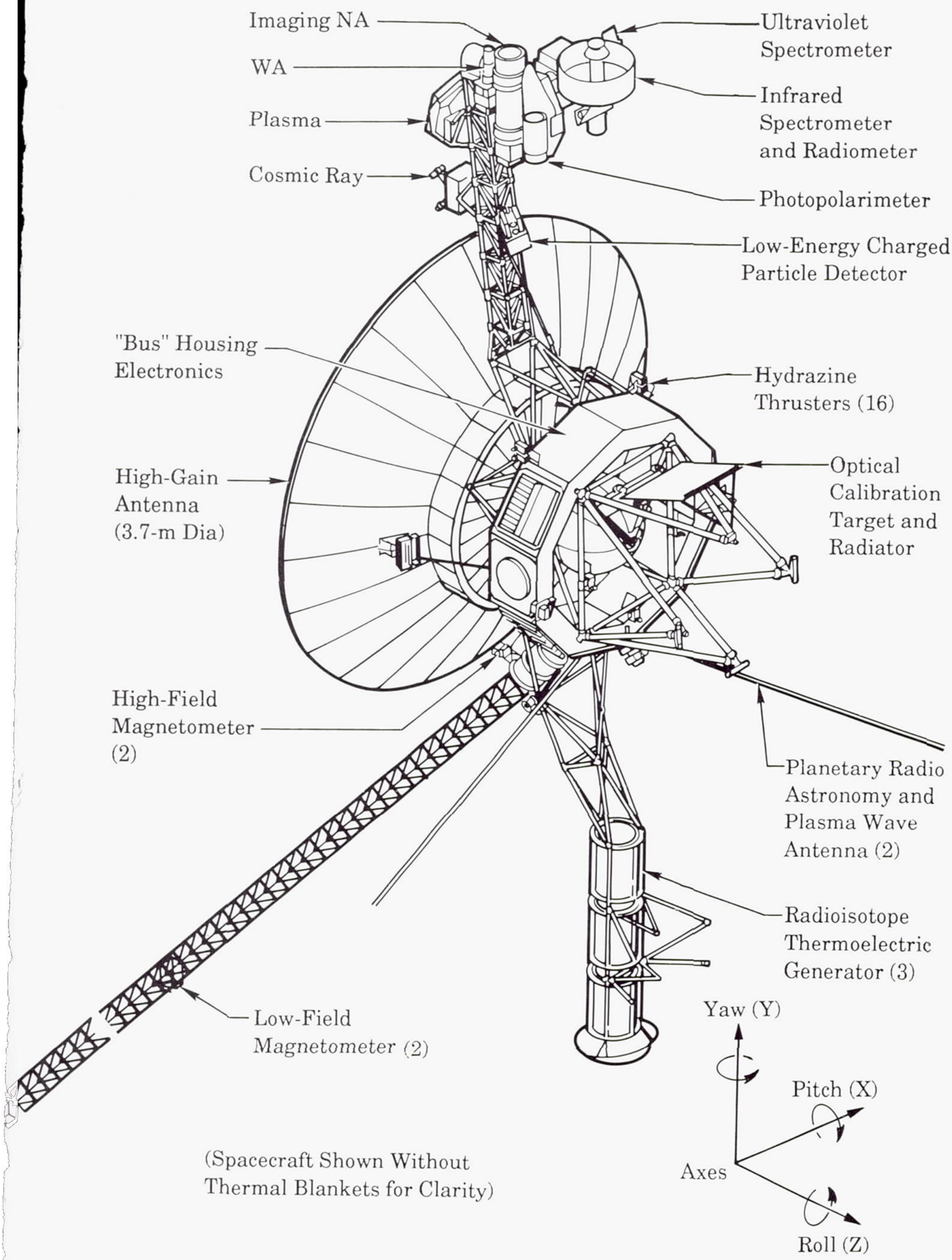


Figure 4-2. The Voyager spacecraft has a launch mass of 825 kg, is nuclear-electric powered, consists of about five million equivalent electronic parts, and uses onboard computer fault detection and response to protect itself.

Spacecraft Attitude Control

Relative to attitude control, the two most common types of spacecraft are spin-stabilized and three-axis-stabilized. The former, such as the Pioneer spacecraft, obtain stabilization by spinning so that the entire spacecraft acts as a steady gyroscope. Three-axis-stabilized spacecraft, such as Voyager, maintain a fixed orientation, or attitude, in space except when maneuvering.

Spacecraft stabilization, as well as spacecraft maneuvering, is controlled by an onboard computer called the Attitude and Articulation Control Subsystem (AACS). This computer also controls scan platform motion.

Voyager has two ways of maintaining its attitude: by gyro control and by celestial control. Gyro control is used for special purposes and short periods of time, up to several hours.

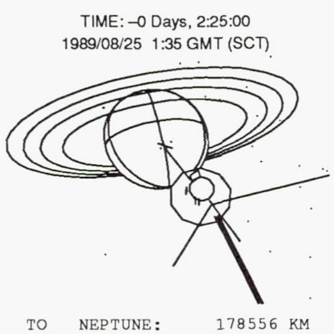
In the celestial control mode, Voyager maintains its fixed attitude in space by viewing the Sun and a bright star such as Canopus, Alkaid, or Achernar. If the spacecraft should drift from its proper orientation by more than a certain angle (called the deadband), the AACS will issue commands to fire the tiny attitude-control thrusters to bring it back to proper orientation (see Figure 4-3). Canopus is used almost exclusively as the reference star by Voyager 2 during interplanetary cruise (Voyager 1 uses Rigel Kentaurus). Canopus, the second brightest star in the sky, is a southern hemisphere star and is barely visible from the southern United States.

The sensor instruments used to track the Sun and star are the Sun Sensor (mounted on the HGA) and the Canopus Star Tracker (CST), so named because Canopus is the preferred star to use whenever possible. Figure 4-3 shows the celestial sensor and gyro accuracies, the limit cycle deadband, and the final scan platform pointing accuracy.

Spacecraft Maneuvers

There are many types of spacecraft maneuvers. We choose one that is fairly simple, and also somewhat common, to use as an example–this is the Stellar Reference Change.

There are times during encounter when Canopus is not suitable as a reference star for Voyager 2. For example, the planet might be on the other side of the bus from the scan platform when Canopus is the lock star. Imaging the planet would then be impossible because spacecraft parts block the view. In this case, an alternate star



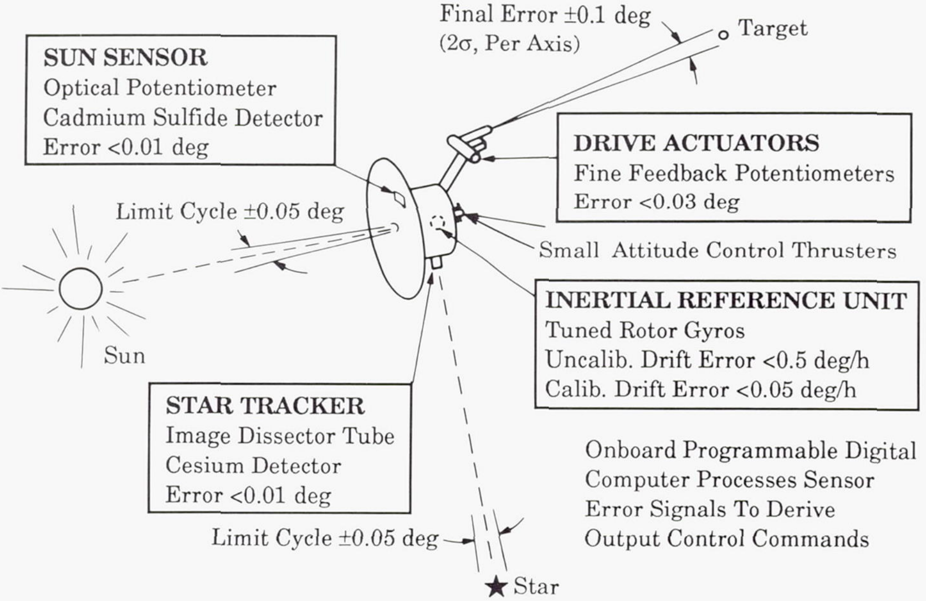


Figure 4-3. When it comes to pointing precision, the Voyager spacecraft is quite a remarkable machine.

(which is on the other side of the sky from Canopus) is chosen, and the Stellar Reference Change maneuver is required.

The maneuver is controlled by the AACS computer. First, the spacecraft goes to gyro control (all-axes inertial mode); then the AACS fires the hydrazine thrusters to start the spacecraft turn about the roll axis. The turn rate is precisely chosen to be either the nominal turn rate (0.18 degrees per second) or a new higher turn rate (0.30 degrees per second).

After the spacecraft has turned through the prescribed angle, the AACS fires the opposite set of thrusters to halt the turn. Since the roll turn is about the axis pointing toward Earth, the Sun will have "coned" around this axis and reached a different spot on the spacecraft's Sun Sensor plate. The Sun Sensor then locks onto the Sun in its new position. (This displacement of the Sun from the roll axis is called the Sun Sensor bias.) Finally, the star tracker locks onto the new reference star, and the spacecraft is returned from gyro control to celestial control.

Scan Platform Pointing

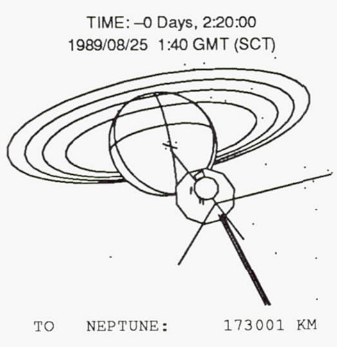
Several appendages are attached to the spacecraft bus. These are the HGA (discussed above), the magnetometer boom, the PRA antennae (rabbit ears), the RTG boom (supplying power), and the scan platform. These are shown in Figure 4-2.

Four of the science instruments are on the scan platform: namely those that need to be pointed at a target body (the planet, a star, rings, or one of the satellites). A glance at Figure 4-2 will show you why it is necessary to mount these instruments on such a long boom. If they were mounted on the bus, they could not look backwards (during post-encounter) because the HGA would block their view. The spacecraft mass distribution is balanced by placing the scan platform on the other side of the bus from the radioactive power source.

The scan platform has motors and gears (called actuators) which slew the platform to point in various directions. If you imagine "up" as being in the direction of the HGA boresight (generally toward Earth), then a motion up or down is accomplished by an elevation slew, and a motion to the right or left is accomplished by an azimuth slew. These are called, for short, El slews and Az slews. The locations and components of the actuators are shown in Figures 4-4 and 4-5.

About 102 minutes after Voyager 2's closest approach to Saturn in 1981, the azimuth motion of the scan platform unexpectedly halted, and science data were lost from the instruments that require pointing. Apparently this seizure was due to heavy use of high-rate slews to move the scan platform at 1 deg/sec. A vital lubricant probably migrated away from a tiny shaft-gear interface (spinning at 170 rpm), resulting in galling (wearing away from friction) and debris buildup, and finally leading to the seizure. Scan platform motion was resumed in two days, but analysis and testing leading to a failure model, to a strategy to monitor the actuator's health, and to guidelines for safe use of the actuator were completed over three years.

Needless to say, the faster slews will not be used during the Neptune encounter, except for eight medium-rate (0.33 deg/sec) slews used to capture critical science observations. All other slews will not exceed the low rate of 0.08 deg/sec. Nevertheless, the scan platform motion will be monitored quite closely by the Torque Margin Test (see Chapters 8 and 9). A contingency near-encounter sequence (R951) has been prepared for use just in case an azimuth actuator problem is experienced.



Power Subsystem

Spacecraft electrical power is supplied from three Radioisotope Thermoelectric Generators (RTGs), which are miniature nuclear power plants that convert about 7000 watts of heat into some 400 watts of

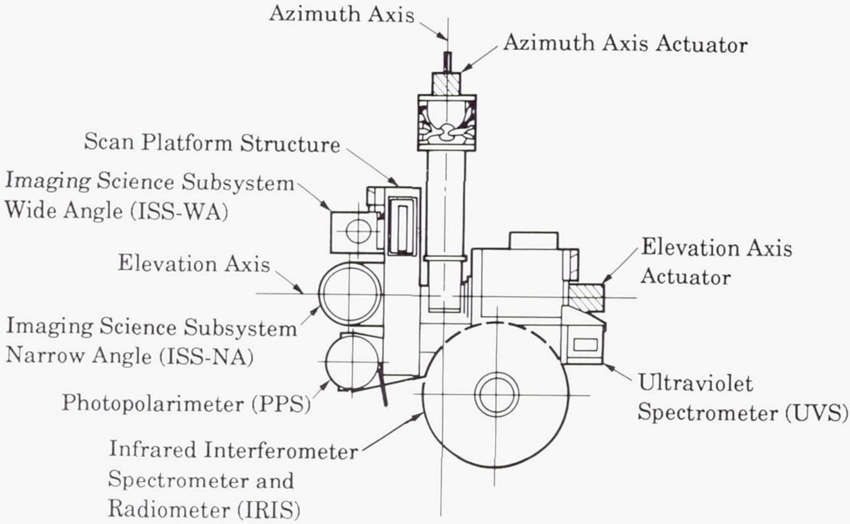


Figure 4-4. This view of the Voyager scan platform shows the locations of the two electric motors and gear trains, known as "actuators," that drive the platform to look in different directions.

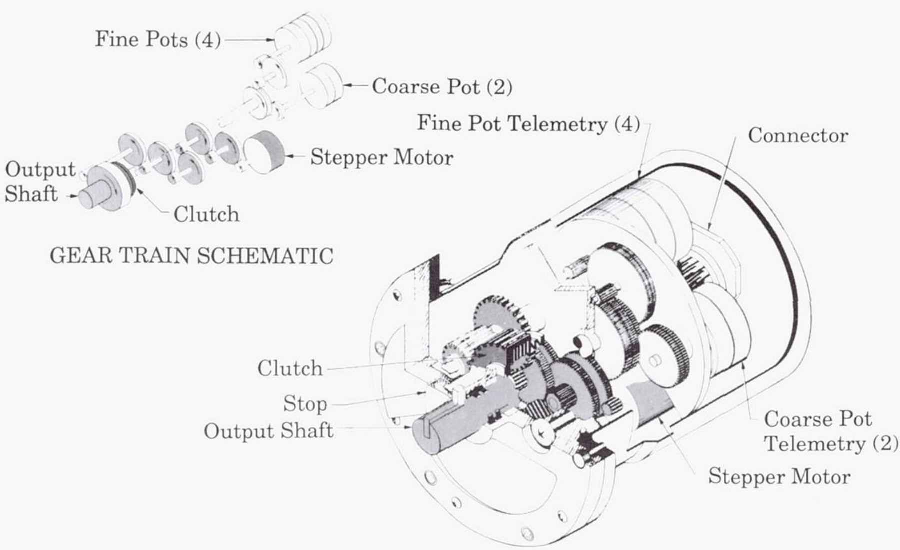


Figure 4-5. Small electric motors drive the Voyager scan platform about "azimuth" and "elevation" axes. Voyager 2's azimuth actuator stuck shortly after the Saturn encounter, but was used for the Uranus encounter and will be used for the Neptune encounter.

electricity. These lie along the RTG boom, away from the spacecraft bus and opposite the scan platform (see Figure 4-2.)

At launch the power output from the RTGs was 475 watts. However, the power output decreases by about 7 watts each year due to several causes, including the half-life of the fissionable plutonium dioxide and degradation of the silicon-germanium thermocouples. By the time Voyager 2 reaches Neptune, the RTG power output will be down to about 370 watts.

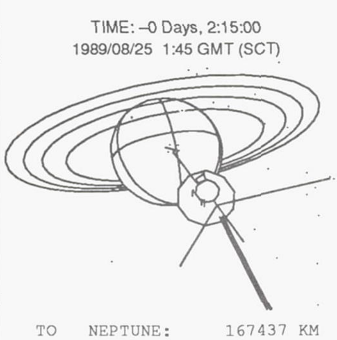
The spacecraft power load is constrained to be less than the RTG output, and excess power is dissipated through the shunt radiator as heat. The difference between the available power and the power used in running the spacecraft is called the "power margin." Since the power available is substantially less for Neptune than for previous encounters, great care is taken to plan the power management strategy. For example, the S-band high-power state is no longer used.

Project guidelines require that this power margin be kept fairly large (above 12 watts) as a safeguard against power surges or miscalculations which might cause the spacecraft to try to draw more power than is available. But, were this to happen, the onboard computer has a fault protection algorithm (FPA) that could turn off power to some subsystems to reduce power consumption. This would be a major inconvenience and, if it happened during encounter, would cause loss of science data.

Data Storage Subsystem

There are occasions when the Voyager spacecraft cannot immediately send science telemetry data to Earth. These occasions could occur during a spacecraft maneuver when the HGA is not pointed at Earth, or during the time the spacecraft is behind the planet as seen from Earth (Earth occultation). Also, it is no longer possible to send certain types of data (such as PWS and PRA high-rate frames) directly into the telemetry stream because the data rate is too high to be received without error. In all these instances, the Digital Tape Recorder (DTR) is available to store the data for later playback to Earth.

The DTR has three speeds in use at Neptune encounter. But, rather than citing the speed in inches per second, as for conventional tape recorders, the speed is cited in units of information per second, kilobits per second (Kbps). The three speeds are 115.2 Kbps (record only), 21.6 Kbps (playback only), and 7.2 Kbps (both record and playback). There are eight tracks on the DTR. Each of these can hold up to 12 images if only



images are recorded. This is seldom the case, since data from other instruments need to be recorded also.

As you can imagine, the experimenters often like to record more data than the tape recorder has the capability to store. Thus, DTR data management is a critical concern. It is important to play the data back quickly so that the tape recorder can be filled again. But, playbacks interfere with science gathering and require certain DSN configurations that are not always available. So data management during busy periods remains a challenging task.

Spacecraft Receiver

Periodically, instructions are sent (uplinked) from the ground to the spacecraft. These instructions, called commands, are modulated (superimposed) onto the radio signal and are transmitted at 16 bits per second by one of the DSN tracking stations. Traveling at the speed of light, they will reach the spacecraft at Neptune in just over four hours. The radio signal carrying the commands is received by the spacecraft HGA and sent to the receiver. The receiver extracts the command subcarrier from the carrier signal and sends it to the Command Detector Unit (CDU). Here the commands are demodulated (removed from the subcarrier) and converted to digital form. The commands are then sent to the Computer Command Subsystem (CCS).

On April 6, 1978, a failure protection algorithm in Voyager 2's CCS automatically switched from the prime to the backup receiver. But a tracking loop capacitor had failed in the backup receiver. Soon after a commanded return to the prime receiver, the prime receiver suddenly failed. Seven days later, the fault protection algorithm switched back to the crippled backup receiver. Because of these two failures, more complicated procedures are used for commanding Voyager 2 than are used for Voyager 1.

The receivers were designed to lock onto the signal in order to follow shifts in frequency, but this function is no longer possible on Voyager 2. (These shifts in frequency are Doppler shifts that result from changes in the relative velocity between the spacecraft and the DSN antenna, due primarily to the Earth's rotation.) In commanding Voyager 1, for example, the DSN transmits at a constant frequency and the receiver locks onto and follows the moving frequency.

However, for Voyager 2, the failed tracking loop capacitor makes it necessary for the *received* signal to be at a constant frequency. To accommodate the Doppler shifts, it is then necessary for the DSN tracking station to transmit a moving frequency. If the transmitted frequency is not within 96 Hertz (cycles/sec) of the receiver rest frequency, then Voyager 2 will turn a deaf ear on instructions from Earth. Furthermore, an unpredicted temperature change of as little as 0.25° C (0.45° F) in the receiver will shift the rest frequency by 96 Hertz from its predicted value. Temperature changes in the receiver can be caused by a change in the spacecraft's power status or by the Sun's heat on the receiver bay. The Spacecraft Team may schedule a "command moratorium" period up to 48 hours before or after critical events to assure that the receiver temperature has had a chance to stabilize. All of these factors complicate the process of sending commands to Voyager 2.

If the second receiver were to fail, there would be no way to command the spacecraft to execute further activity. We would not be able to point the scan platform instruments at their targets nor point the HGA at Earth. We could not have a successful encounter. To protect against failure of the remaining receiver, a special CCS Load has been placed in the CCS. This contingency Back-up Mission Load (BML) contains a few commands that will allow some science to be gathered in the event that the regular encounter CCS Loads cannot be received by the spacecraft because of receiver failure. There are several designs for BMLs, each resident in the CCS over a different interval of time.

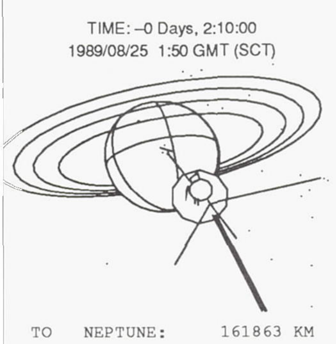
As serious as all this sounds, remember that despite these problems, Voyager 2 has so far completed successful encounters with Jupiter, Saturn, and Uranus, and has begun its task of revealing the mystic Neptune.

Computer Command Subsystem (CCS)

The CCS consists of two identical computer processors, their software algorithms, and some associated electronic hardware. The CCS is the central controller of the spacecraft (the brain of the spacecraft, if you will). Figure 4-6 shows the CCS in relation to the AACS and Flight Data Subsystem (FDS) computers, as well as to the DTR (the main component in the Data Storage Subsystem) and other subsystems.

The CCS has two main functions: to carry out instructions from the ground to operate the spacecraft and gather science data; and to be ever alert for and to respond to any problem with any of the spacecraft subsystems.

The latter of these CCS functions is carried out by a series of software routines called Fault Protection Algorithms (FPAs). These algorithms, which occupy roughly twenty percent of the CCS memory, make the spacecraft semi-autonomous and able to act quickly to protect itself. This is important because of the long delay time



required for a response to the problem from Earth: over eight hours round-trip light time (at Neptune closest approach), plus the reaction time of the engineers to detect the problem and prepare the proper response. In many instances such a delay would be intolerable.

The other CCS function, storing and processing commands from Earth, allows the spacecraft to act as an intelligent robot to carry out its science-gathering functions in strict accordance with the carefully developed mission plan.

It is convenient to send up one transmission to the spacecraft which contains most or all of the commands needed to operate it for periods of time ranging from 30 days during the Observatory Phase to only two days during Near Encounter. Each of these transmissions nearly fills the remaining (non-FPA) memory in the two CCS computers. The contents of each of these transmissions is called a CCS Load and is given an identifying number. "A" loads refer to Voyager 1, and "B" loads to Voyager 2; for example, A821, B901, B902, etc. Chapter 6 contains a timeline which shows each of the encounter CCS Loads.

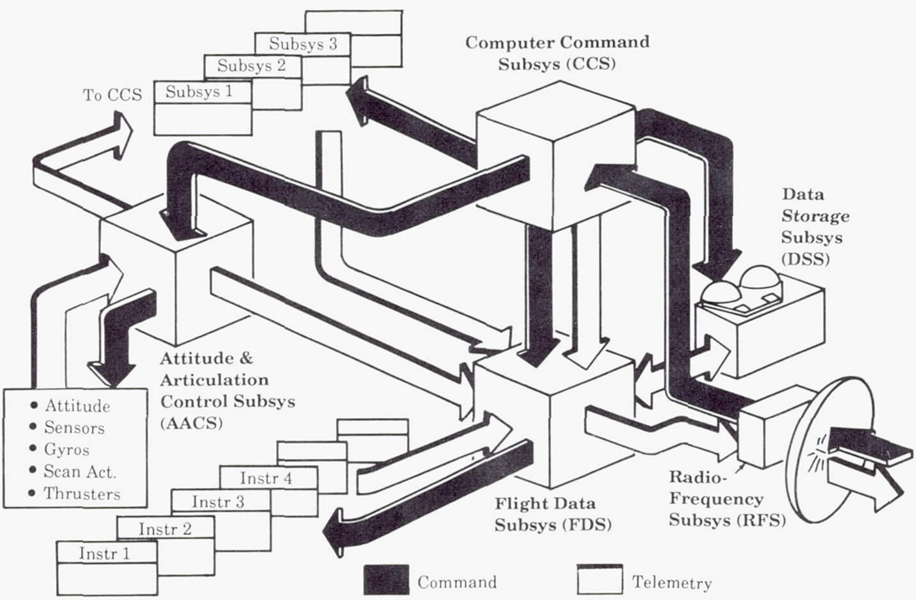


Figure 4-6. Voyager's three computer subsystems contain nearly 33,000 words of memory storage, with the Computer Command Subsystem (CCS) directing most of the activities.

Flight Data Subsystem (FDS)

The onboard FDS, comprising two reprogrammable digital computers and associated encoding hardware, collects and formats the spacecraft's science and engineering telemetry data for transmission to Earth.

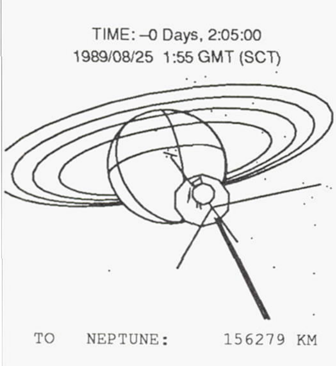
The engineering data, generally at 40 bits per second, are on the S-band downlink and are embedded in science telemetry data on the X-band downlink as well. Engineering data provide the status of the instruments, health of the various spacecraft subsystems, and spacecraft attitude and scan platform position.

The science data (the results of the science observations) are on the high-rate data channel (4.8 to 21.6 Kbps) and are downlinked only on X-band.

The FDS "encodes" the telemetry data by adding redundant bits to the telemetry data in such a way that bits lost in the static may be reconstructed (i.e., intelligently guessed at). For example, the Golay encoding process adds 3600 bits to every 3600 bits of raw science data telemetered to Earth. However, the more efficient Reed-Solomon encoding process only adds 1200 bits to every 3600 bits of raw science data sent to Earth. (See Chapter 9 for further discussion of encoding.)

The FDS also does some special data processing on the picture data in a process called image data compression (IDC), described in Chapter 9. Rather than use the secondary FDS processor as a "hot backup" for the primary computer (both containing identical software), the FDS computers are used in a "dual processor mode" in which the primary unit samples and formats the general science data, while the secondary unit compresses the imaging data. Here, the two processors work in parallel and each performs different functions, effectively doubling the computer memory available for computing tasks.

The FDS also provides appropriate instrument control for the science instruments and the digital tape recorder. For example, control data for the imaging instruments in an "imaging parameter table" in FDS memory provides instructions for imaging shutter modes, filter choices, and exposure levels for each camera.



One of Voyager 2's FDS computer memories has lost a block of 256 memory locations, out of a total of 8192. This is a rather minor failure. However, the loss of 512 more words from the primary memory would be serious, for it would mean we would have to abandon the dual processor mode, and hence, the valuable IDC capability.

Science Instruments

There are eleven scientific investigations on Voyager 2, and the locations of their instruments are shown in Figure 4-2. Figure 5-5 gives sketches and brief descriptions of each of the instruments. Of these, only four are not located on the scan platform or its supporting boom. The Magnetometers use their own boom; the Planetary Radio Astronomy (PRA) experiment shares the rabbit ear antennas with the Plasma Wave Subsystem (PWS); and the Radio Science Subsystem (RSS) uses the radio beams from the HGA.

The four instruments on the scan platform require accurate pointing; these are the Imaging Science Subsystem (ISS) wide- and narrow-angle cameras, the Ultraviolet Spectrometer (UVS), the Infrared Interferometer Spectrometer (IRIS), and the Photopolarimeter Subsystem (PPS). Figure 5-6 shows the relative fields of view of these instruments, and their pointing offsets from each other. These instruments may all make observations simultaneously.

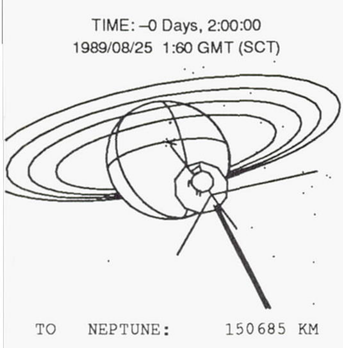
Note the long, rectangular UVS slit. For some observations this slit needs to be aligned in a particular direction, requiring a spacecraft roll maneuver.

The remaining three instruments, mounted along the scan platform boom, are fields and particles experiments. These are the Cosmic Ray Subsystem (CRS), the Low-Energy Charged Particle experiment (LECP), and the Plasma Subsystem (PLS).

All of these experiments (except RSS) send their observational data to the FDS to be formatted into telemetry. All of them, except RSS and ISS, contribute data to a telemetry format called "general science and engineering" (GS&E). This GS&E telemetry data mode has a downlink data rate of 4800 or 7200 bps, depending on the type of encoding the FDS uses, but the information content (symbols per second) is 3600 bps. The PRA, for example, contributes 266 bps, and the IRIS contributes 1120 bps, out of this total of 3600 bps.

The ISS has several data formats of its own at higher data rates because of the large number of data bits required to define a picture (5.12 million, if uncompressed!). Real-time data rates of 8400 and 14,400 bps allow the images to be immediately returned to Earth in the telemetry stream. Non-compressed images may be recorded on the tape recorder at 115,200 bps, then returned to Earth at a later time at a slower playback rate. Two other experiments, PRA and PWS, can also provide a high data rate, and periodically short bursts of these data are put onto the DTR at 115,200 bps for later playback at a slower rate.

As you can see, the Voyager spacecraft is a sophisticated machine. It must have a broad spectrum of capabilities to deliver the scientific sensors to their desired target geometries, collect the scientific data, and return these data to Earth. The scientific sensors are its vital payload and are sophisticated devices, as we shall see in Chapter 5.



The most beautiful experience we can have is the mysterious. It is the fundamental emotion that stands at the cradle of true art and true science.

Einstein

5. SCIENCE SENSORS

In Chapter 2, you prepared a shopping list of things you would like to find out about the Neptune realm. You know that everything you learn comes via one of your four senses. The Voyager spacecraft has 11 sets of sensory devices, which can be conveniently divided up into two types: those that point at something (called target body sensors) and those that don't (called fields, waves, and particles sensors). There are five sets of target body, one fields, two waves, and three particles sensors.

This chapter contains a description of *how* each of the sensors works, a summary of their engineering characteristics, what types of new knowledge each of the sensors can provide, and finally, a wrap-up discussion of the fundamental physics upon which the sensors are based.

Imaging Science Subsystem (ISS)

Humans, like most of Earth's creatures, have evolved with the ability to see a certain kind of light, called visible light. There are many other types of "light" which are invisible to our eyes, such as ultraviolet, infrared, and radio waves. It is most natural, therefore, when sending a spacecraft off to unknown places, for humans to include at least one sensor that is sensitive to visible light. Voyager has two sets of science sensors designed primarily for visible light operation: the Imaging Science Subsystem (ISS) and the Photopolarimeter Subsystem (PPS).

The ISS consists of two "TV" cameras and associated control electronics. The ISS functions much like a pair of video cameras. Both the ISS and a video camera work on exactly the same principle of nature by recording the intensity of light reflected or emitted from the object one is photographing. A video camera converts the light into electronic signals which are recorded on a video cassette (both of these functions are performed by a camcorder). The ISS also converts the light into electrical signals, which are either sent directly to the Earth or stored by the spacecraft on the equivalent of a VCR.

With a normal video camera you have the ability to configure the camera to take a wide variety of pictures under a wide variety of circumstances. Available to the photographer are various lenses, filters, aperture settings, exposure times, and framing speeds. The ISS has many of the same capabilities.

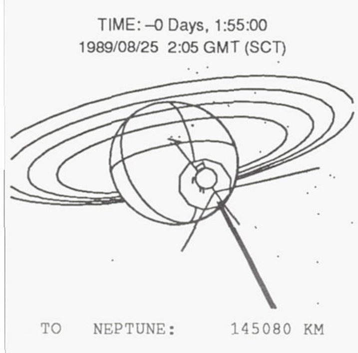
Instead of interchangeable lenses, the ISS has two separate cameras: one with a 200mm focal length lens of 60mm aperture and the other with a 1500mm focal length lens of 176mm aperture. To an Earth-based photographer, both would be considered telephoto cameras (normal focal length being 55mm), but to the Voyager Imaging Team the former is known as the "wide-angle" camera and the latter is known as the "narrow-angle" camera. On each ISS camera, the lens is fixed. The ISS has the ability to shutter pictures one after another or to shutter pictures at widely separated times.

Each ISS camera has eight different filters. Each camera has a "clear filter" that permits the greatest amount of light to pass through to the light-sensitive surface. The other filters permit specified types of light to pass through and block all other types of light from reaching the camera's detector. Both cameras have violet, blue, orange, and green filters. The narrow-angle camera also has an ultraviolet filter and duplicate clear and green filters. The wide-angle camera contains three filters explicitly designed to detect sodium near Io, methane at both Jupiter and Saturn, and methane at Uranus and Neptune, respectively.

Both ISS cameras are fixed aperture devices. However, one may vary the exposure time from 0.005 seconds to 61 seconds. Time exposures which are longer than normal exposures by integer multiples of 48 seconds are also possible. This capability is critical because the sunlight reaching Neptune is roughly 36 times dimmer than at Jupiter. The ISS cameras store pictures in the form of electrical impulses. The primary differences between the ISS and the familiar video cameras are the number of scan lines, the time required to scan the image, and the way color is produced. The ISS has 800 scan lines, while camcorders typically have only 525. The ISS needs from 48 seconds to several minutes to "read out" the image, while video cameras scan an image 60 times each second.

Concerning color, video cameras do this very easily, while the ISS must take black and white pictures through three different color filters. After reconstruction back on Earth, the composite photograph can be in "natural" color—that is, what the human eye would see. However, it can also be processed to greatly enhance color contrast or to represent the scene in "false color" to emphasize particular features.

The ISS is used to observe and record the visible characteristics of planets, atmospheres, moons, and rings. These visible characteristics include the sizes, colors, brightnesses, and surface textures of these objects. In addition, groups of ISS pictures are used to map the surfaces of moons.



The Voyager Navigation Team uses ISS pictures of various moons against backgrounds of stars with known positions to accurately determine where the spacecraft was located at the time the picture was taken. This technique is known as optical navigation.

Infrared Interferometer Spectrometer and Radiometer (IRIS)

The IRIS is a very specialized type of light meter. It comes equipped with a large, permanently attached reflecting telescope.

The IRIS uses a sensor that can "see" infrared light. Infrared means less than or below red. Infrared is light that is next to and below (in frequency) the red light that our eyes can see. The IRIS actually acts as three separate instruments. First, the IRIS is a very sophisticated thermometer. Second, the IRIS is a device that can determine when certain types of elements or compounds are present in an atmosphere or on a surface. Third, it uses a separate radiometer to measure the total amount of sunlight reflected by a body at ultraviolet, visible, and infrared frequencies.

Any solid, liquid, or gas that has a temperature above absolute zero emits heat energy. The amount and "color" (wavelength) of heat energy that the substance emits is dependent, among other things, upon its temperature. The IRIS can determine the distribution of heat energy a body is emitting, which then allows us to determine the temperature of that body or substance. In the special case of an atmosphere, the IRIS can determine the temperature of the atmosphere at various altitudes, producing what is called a temperature profile.

By measuring the total amount of heat energy that a planet is emitting and the total amount of sunlight reflected, and comparing this to the total amount of energy received from the Sun, scientists can determine if heat from the interior of the planet is escaping. Jupiter, Saturn, and Neptune emit about twice as much heat energy as they receive. Mercury, Venus, Earth, Mars, and Uranus show little or no evidence of heat generated in their interiors and, therefore, reradiate to space very nearly the same amount of heat energy they absorb from the Sun.

The IRIS can also determine if certain elements and molecules are present in a particular atmosphere or on a particular surface. The physical principle that permits this type of element/molecule determination is the following. Remember that atoms consist of one or more protons plus neutrons (only hydrogen has no neutrons) in a nucleus, surrounded by the same number of "orbiting" electrons as there are protons. Molecules consist of two or more atoms bound together by electrical forces. Light energy (for example, from the Sun) may be absorbed by an atom or molecule, which then becomes

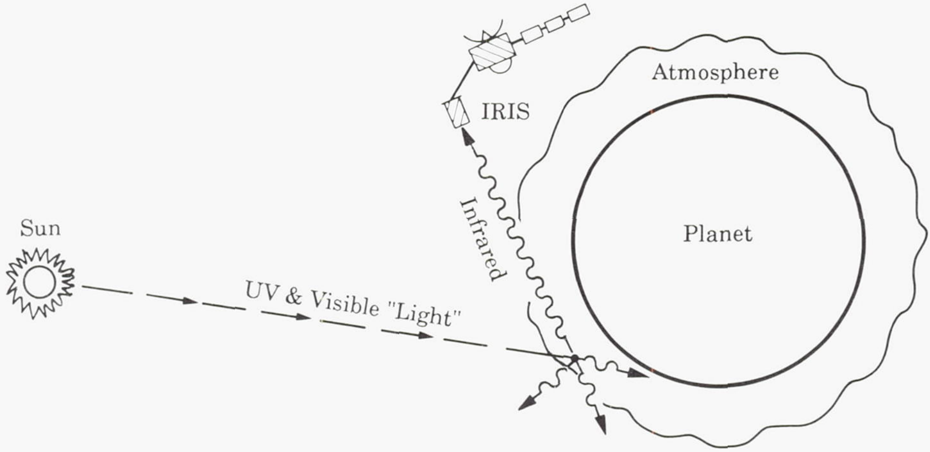


Figure 5-1. The planet absorbs the visible and ultraviolet energy from "sunlight," then emits infrared "light" which the IRIS can "see." Certain molecules in the cooler, overlying atmosphere absorb some colors of infrared "light."

unstable because it has excess energy. The atom or molecule releases the excess by emitting the energy (Figure 5-1). If the emitted energy is infrared energy, the IRIS can detect the emission. Continuous infrared (heat) energy being emitted from deeper, warmer layers of an atmosphere is selectively absorbed at discrete infrared colors by the cooler overlying atmosphere.

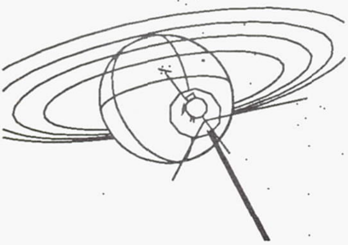
Each atom or molecule will emit or absorb energy of one or more colors. It is known from laboratory studies what colors are emitted or absorbed by a particular element or compound. To detect this element or compound, all you have to do is see the appropriate color or colors being emitted or absorbed in the infrared data collected by IRIS.

Using this procedure, IRIS has detected hydrogen, helium, water, methane, acetylene, ethane, ammonia, phosphine, and germane in the atmospheres of Jupiter, Saturn, and Uranus.

Ultraviolet Spectrometer (UVS)

The UVS is also a very specialized type of light meter that is sensitive to ultraviolet light. "Ultraviolet" means more than or beyond violet. Ultraviolet light is next to and above (in frequency) the violet light that our eyes can see. Sunburns and suntans are caused by ultraviolet light.

The UVS is used to determine when certain atoms or ions (electrically charged atoms) are present, or when certain physical processes are going on.



It works on the same physical principle as the IRIS. However, instead of using a lens, the UVS limits the area of sky it looks at by using a series of “blinders” called aperture plates. The UVS looks for specific colors of ultraviolet light that certain elements and compounds are known to emit or absorb.

The Sun emits a large range of colors of light. If sunlight passes through an atmosphere, certain elements and molecules in the atmosphere will absorb very specific frequencies of light. If the UVS, when looking at filtered sunlight, notices the absence of any of these specific colors, then particular elements and/or compounds have been detected. This process is called identifying elements or compounds by atomic absorption (Figure 5-2).

The UVS can only use the atomic absorption technique when it is in a position to look back at the Sun (or a suitably bright star), through a planetary or satellite atmosphere or through a collection of ring particles. This geometry is called a solar (or stellar) occultation.

The UVS has used these emission and absorption techniques to detect hydrogen, helium, methane, ethane, acetylene, sodium, sulfur, nitrogen, and oxygen. The UVS, like IRIS, has been used to detect most of the gases and their photochemical products found in the atmospheres of the giant planets, though at much higher levels in the atmosphere.

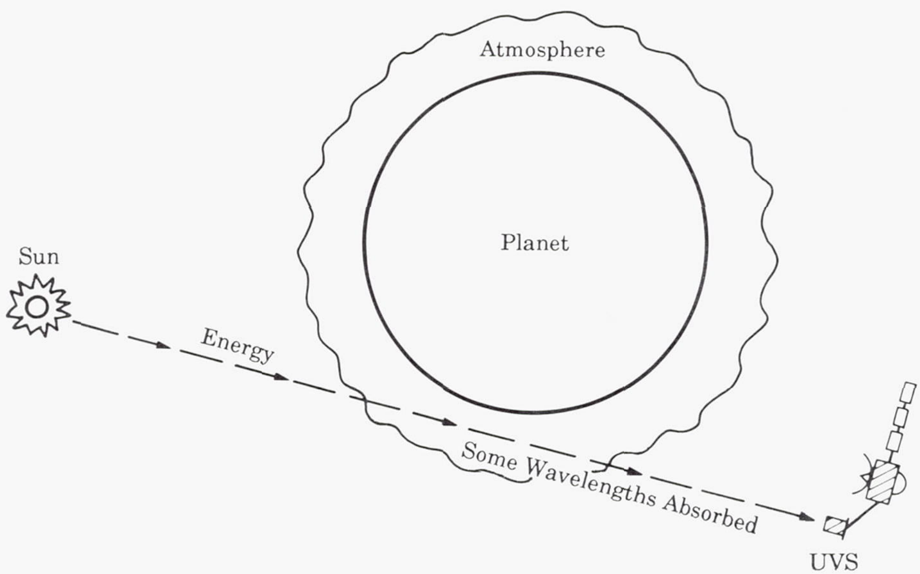


Figure 5-2. Certain molecules in the atmosphere can absorb particular wavelengths from the Sun’s energy, and the UVS can spot these missing “lines.”

Under certain conditions, the UVS is sensitive to energy that is emitted when lightning occurs, when an auroral display is going on, or from particles independently orbiting the planets.

The UVS can also be used to study the stars. It can determine when certain elements are present in various stars and measure the temperatures of extremely hot stars. The UVS instruments on both Voyagers have been used for years as stellar observatories because they can see colors completely blocked by the Earth's atmosphere. The UVS is making fundamental contributions to ultraviolet astronomy.

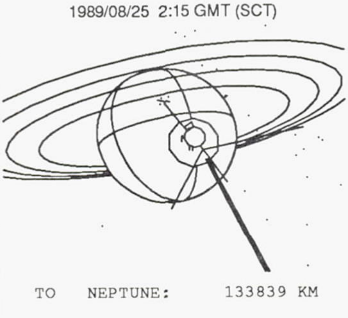
Photopolarimeter Subsystem (PPS)

The PPS is the fourth of the specialized light-measuring devices on board Voyager. The PPS is very much like the ISS narrow-angle camera in that it has a very high magnification reflecting telescope. It is unlike the ISS narrow-angle camera in that each PPS measurement produces one picture element (pixel), whereas each ISS image consists of 800 lines, with each line consisting of 800 pixels. Of the Voyager science sensors that are primarily sensitive to visible light (the two ISS cameras, the IRIS radiometer, and the PPS), the PPS is by far the most sensitive.

The PPS allows the most flexibility in adapting to varying circumstances. It has four aperture settings, three color filters, and four polarizing filters. It also has two commandable sensitivities.

The PPS studies how light changes as it is reflected from or absorbed by objects of interest. Such "objects" include the surfaces of moons, tiny aerosol particles in an atmosphere, and ring particles. The PPS can infer the texture and composition of a solid surface; the density, particle sizes, and composition of a planetary ring; and the existence, particle sizes, and composition of atmospheric hazes.

The PPS is ideally suited for observing stellar occultations (Figure 5-3). The PPS is sensitive enough to light to be able to track a star as it moves behind planetary rings or the thin part of a planetary or satellite atmosphere. Planetary rings are a collection of countless small objects in orbit about a planet. Since there is space between the ring particles, light can pass through the rings. The PPS is used to record the rapid variation of brightness from a star as it passes behind a set of rings. The fraction of starlight that passes through is an indication of how "transparent" the rings are and where gaps are located. The PPS stellar



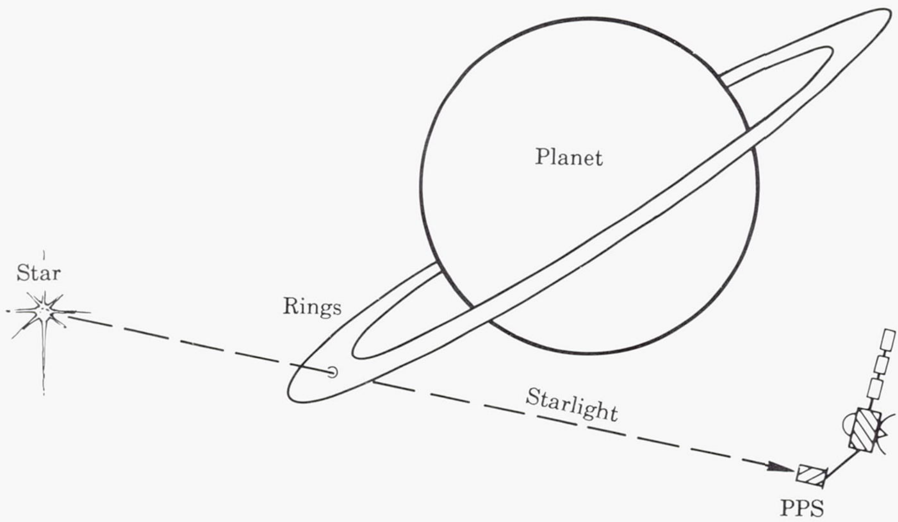


Figure 5-3. Like watching a flashlight moving behind a partially transparent picket fence, the PPS can accurately measure the amount of starlight passing through a planetary ring system.

occultation technique produced a bounty of information about the complex structure of the rings of Saturn and Uranus.

Radio Science Subsystem (RSS)

All of the sensors on the spacecraft, except for the RSS, are called passive sensors. A passive sensor must wait for energy or particles to come to it before it can see anything. A passive sensor must have another source create the energy or particles that it sees. The RSS is an active sensor. An active sensor provides both its own energy and the detector to measure the effect of the target of interest on the energy.

The energy source for the RSS is the same radio transmitter that is used for communications between the spacecraft and the Earth. The Radio Science detectors are located at Deep Space Network (DSN) tracking stations on Earth. The RSS is capable of transmitting stable carrier frequencies at both S- and X-band using an Ultra-Stable Oscillator (USO) on board the spacecraft. To achieve even more stable carrier frequencies, the RSS can receive and retransmit an extremely precise signal sent from the DSN antennas. Four distinct types of experiments have been performed using the RSS.

The RSS is used to probe both planetary and satellite atmospheres. When the spacecraft is passing behind a planet or a moon with an atmosphere, the spacecraft's radio signal is beamed through that atmosphere. The signal will be bent and slowed by the atmosphere by a process called

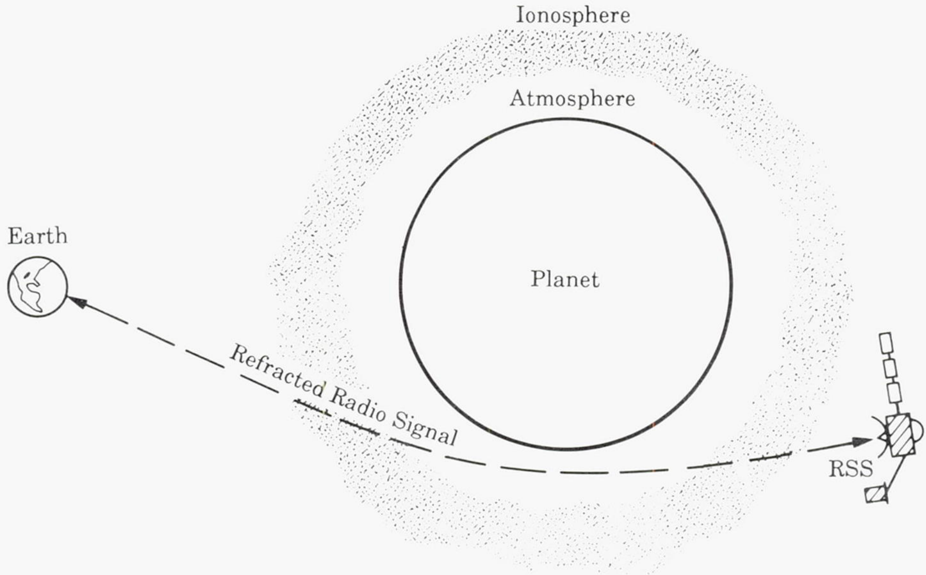
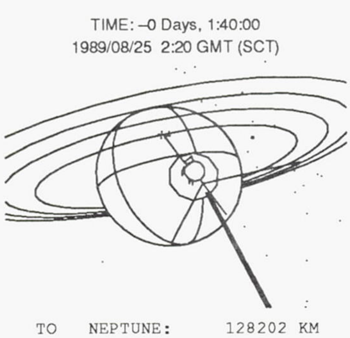


Figure 5-4. The Radio Science Subsystem uses the spacecraft's radio transmitter to beam a signal through a body's ionosphere and neutral atmosphere for detection by the DSN antennas on Earth. The signal changes allow an estimate of the density, temperature, pressure, and composition of the atmosphere.

refraction. The spacecraft antenna is pointed such that the bent radio signal reaches the Earth (Figure 5-4). This viewing geometry is called an Earth occultation.

From the changes in the frequency and the intensity of the X- and S-band signals, the temperature, pressure, density, and composition of the atmosphere at different altitudes can be calculated. If an ionosphere exists outside the atmosphere, it will also change the radio signal. Studies of the corona of the Sun are carried out in a similar fashion when the spacecraft passes behind or near the Sun as viewed from Earth.

The second type of RSS experiment involves directing the X-band radio signal through planetary rings. When the spacecraft is behind a set of planetary rings (from an Earth perspective), the antenna is pointed directly at the Earth. The signal passes through the rings and is received on the Earth. Changes in the X- and S-band signal intensities and frequencies can be used to estimate the number, width, shape, and thickness of rings, and the sizes of the particles that make up rings.



The third type of RSS experiment is the determination of the mass of a planet or moon that the spacecraft passes at close range. This experiment works on the Doppler principle. The spacecraft's radio transmitter sends a signal at a well-known stable frequency. Any change in speed (acceleration) that the spacecraft experiences will cause the frequency of the radio signal received by DSN antennas on Earth to change. The amount of frequency change (the Doppler shift) is dependent on the change in speed of the spacecraft, relative to Earth.

When the spacecraft passes close to a planet or moon, that body pulls on the spacecraft, causing its speed to increase during approach and to decrease during departure. The amount of change in speed depends only upon the mass of the planet or moon and the distance of the spacecraft from the planet or moon. Thus, by measuring the change in frequency of the Earth-received radio signal, the mass of the planet or moon can be estimated.

The final RSS experiment is a test of general relativity. The Theory of General Relativity predicts an apparent slowing in the speed of a radio signal when the signal passes near any massive body. Each time the Voyager spacecraft signal passes close to the Sun (the most massive solar system body), the radio signal is delayed. This observed delay is compared to that predicted by the Theory of General Relativity. So far, general relativity has passed the test each time.

Fields, Waves, and Particles Experiments

The fields, waves, and particles experiments are organized as six science investigations. The Planetary Radio Astronomy (PRA) Subsystem is designed to measure radio waves from the Sun and planets. The Plasma Wave Subsystem (PWS) detects radio waves generated near the spacecraft. The Magnetometer (MAG) Subsystem measures the strength and orientation of magnetic fields through which the spacecraft is passing.

The remaining science investigations measure charged particles of various energies. They include the Plasma Subsystem (PLS), the Low-Energy Charged Particle Subsystem (LECP), and the Cosmic Ray Subsystem (CRS).

Planetary Radio Astronomy (PRA)

The PRA is a sophisticated radio receiver, attached to a pair of 10-m (33-ft) "rabbit ears". The PRA listens for radio signals produced by the Sun and the planets, their magnetospheres, and lightning. The Jovian, Saturnian, and Uranian systems all produced such signals.

The PRA works in one of two ways. Suppose you had three favorite radio stations, but that you were a compulsive button pusher. As the PRA switches among three single (programmable) frequencies, dwelling on each for only six seconds, it would be like pushing your favorite radio buttons every six seconds.

Consider, however, a second case. Suppose you knew that there was going to be a college football game broadcast at 1 PM on Saturday, but you didn't know the station. You would start your radio receiver at the extreme left end of the radio dial, and sweep across. You would stop at each station long enough to recognize the signal. If it wasn't the game, you would pass on to the next station. If none of the stations were broadcasting the game (perhaps because it was on FM and you are tuning the AM band), you would have surveyed the entire band. This is how the PRA works in its scanning mode, except that it starts at the higher frequencies and sweeps down. Because it senses signals from each of its "rabbit ear" antennas separately, it can also detect the polarization (vibration pattern) of the radio waves.

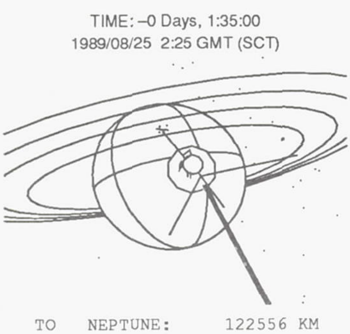
Plasma Wave Subsystem (PWS)

The PWS, like the PRA, is essentially a radio receiver and amplifier. It listens for signals at frequencies that the human ear could hear (audio frequencies), as well as at frequencies slightly above audible. The PWS shares the 10-m pair of rabbit ears with the PRA, but uses them as a single antenna. With an effective length of only 7 m (23 ft) the PWS normally operates in a scanning mode. If you tuned your radio receiver first to one station, then another, then another, up to sixteen stations, you would be operating your receiver as the PWS does when it is scanning.

The PWS has a second mode of operation. It can simultaneously listen to all the stations on its audio band. This mode is used most frequently when the spacecraft is near a planet, and can operate simultaneously with the scanning mode.

The PWS samples the behavior of plasmas in and around planetary magnetospheres by measuring the radio waves generated by those plasmas. It can also detect planetary lightning and the presence of tiny ring particles that strike the spacecraft while it moves through the plane of the rings.

Magnetometer (MAG)



Although the MAG can detect some of the effects of the solar wind on the outer planets and moons, its primary job is to measure changes in the Sun's magnetic field with distance and time, to determine if each of the outer planets has a magnetic field, and how the moons and rings of the outer planets interact with those magnetic fields. If it detects a planetary magnetic field, its job then becomes to measure the characteristics of the magnetic field.

The MAG can be visualized as four sets of compasses. Each set consists of three compasses, mounted at right angles to each other. Two of the compass sets are very sensitive, and can detect magnetic field strengths as weak as 1/10,000 the strength of the magnetic field of the Earth's surface. The other two sets are not nearly so sensitive, and are designed to detect large magnetic field strengths, some 20 times stronger than the Earth's magnetic field. To avoid detecting magnetic fields generated by the spacecraft itself, the more sensitive compasses are mounted twenty feet out and forty feet out on a long boom.

Particle Detectors

The PLS, LECP, and CRS all detect the impact of electrically charged particles. The difference between the three sets of sensors is that the PLS basically looks for the lowest-energy particles, and the LECP and CRS look for higher-energy particles. All three sets of sensors work by sensing particles that hit them.

Plasma Subsystem (PLS)

A "plasma" is a gas or "soup" of charged particles. It typically consists of electrons as well as positively charged nuclei produced when the original atoms lost one or more of their electrons. The PLS looks for the lowest-energy particles. It also has the ability to look for particles moving at particular speeds and, to a limited extent, to determine the direction from which they came. The PLS can be imagined as a piece of wood with a variable amount of syrup in front of the wood. The syrup slows the particle down so that it can just hit the wood and stick to it. Up to a point, if one wants to look for faster particles, one simply puts more syrup in front of the wood. In actuality, the PLS steps through various amounts of "syrup" looking for particles moving at various speeds.

Low-Energy Charged Particle (LECP) and Cosmic Ray Subsystem (CRS)

The LECP and CRS look for particles of higher energy than the PLS, at overlapping energy ranges. The LECP has the broadest energy range of the three sets of particle sensors. The CRS looks only for very energetic particles, and has the highest sensitivity. Both of these sensor sets also have a limited ability to determine the particle directions and compositions.

The LECP can be imagined as a piece of wood, with the particles of interest playing the role of bullets. The faster a bullet moves, the deeper it will penetrate the wood. Thus, the depth of penetration measures the speed of the particles. The number of "bullet holes" over time indicates how many particles there are in various places in the solar wind, and at the various outer planets. The orientation of the wood indicates the direction from which the particles came.

The CRS looks for particles with the highest energies of all. Very energetic particles can often be found in the intense radiation fields surrounding some planets (like Jupiter). Particles with the highest-known energies come from other stars. The CRS looks for both.

The CRS makes no attempt to slow or capture the super-energetic particles. They simply pass completely through the CRS. However, in passing through, the particles leave signs that they were there. Thus, the CRS can be visualized as simply a piece of wood that the bullets pass completely through. One simply counts the "bullet holes", to know when a high-speed particle impacted, and how often. The CRS has seven separate "pieces of wood" oriented in different directions, and looking for different types of high-energy particles.

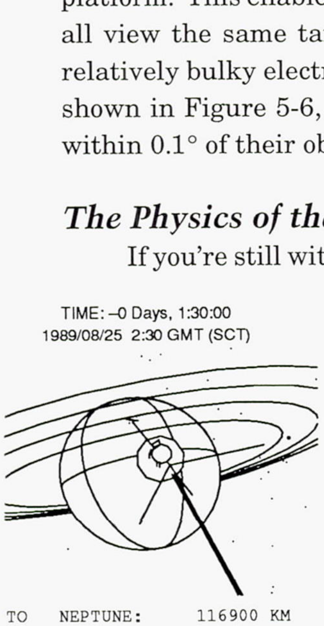
Sensor Engineering Characteristics

Figure 5-5 provides a brief summary of the engineering characteristics of each of Voyager's eleven scientific investigations.

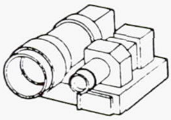
Prior to launch, an attempt was made to perfectly align the fields of view of the optical instruments when they were mounted on the scan platform. This enables them to provide complementary information as they all view the same target. As you might imagine, it is not easy to align relatively bulky electronic equipment to ultra-high precision. However, as shown in Figure 5-6, the alignment mechanics did a first-class job, being within 0.1° of their objective.

The Physics of the Optical Target Body Instruments

If you're still with us, you must be quite interested in how the Voyager sensors help us learn about other worlds. So now is the time for your physics refresher, to tie off some of the basic concepts. The Voyager optical sensors that actually point at something (the ISS, IRIS, UVS, and PPS) all work on the same basic principles of atomic physics.

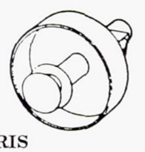


TARGET BODY SENSORS

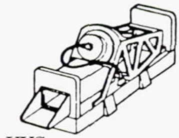


ISS
The Imaging Science Subsystem consists of two television-type cameras, each with 8 filters. One has a 200 mm wide-angle lens with an aperture of f/3, while the other uses a 1500 mm narrow-angle f/8.5 lens.

PPS
The Photopolarimeter Subsystem uses a 0.2 m telescope fitted with filters and polarization analyzers. It covers eight wavelengths in the region between 235 µm and 750 µm.

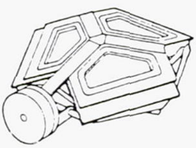


IRIS
The Infrared Radiometer Interferometer and Spectrometer measures radiation in two regions of the infrared spectrum, from 2.5 to 50 µm and from 0.3 to 2.0 µm.

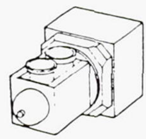


UVS
The Ultraviolet Spectrometer covers the wavelength range of 40 µm to 180 µm looking at planetary atmo- spheres and interplanetary space.

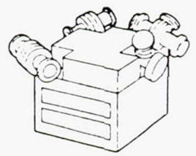
FIELDS, WAVES, AND PARTICLE SENSORS



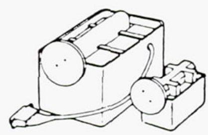
PLS
The Plasma Subsystem studies the properties of very hot ionized gases that exist in interplanetary regions. One plasma detector points in the direction of the Earth and the other points at a right angle to the first.



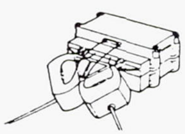
LECP
The Low-Energy Charged Particle experiment uses two solid-state detector systems mounted on a rotating platform. The two subsystems are the low energy particle telescope (LEPT) and the low energy magnetospheric particle analyzer (LEMPA).



CRS
The Cosmic Ray Subsystem detector measures the energy spectrum of electrons and cosmic ray nuclei and uses three independent systems: a high-energy telescope system (HETS), a low-energy telescope system (LETS), and an electron telescope (TET).



MAG
The Magnetic Fields experiment consists of four magnetometers: 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 magnetometers mounted on the body of the spacecraft.



PWS and PRA
Two separate experiments, the Plasma Wave Subsystem and the Planetary Radio Astronomy experiment, share the two long antennas which stretch at right-angles to one another, forming a "V". The PWS covers a frequency range of 10 Hz to 56 kHz. The PRA receiver covers two frequency bands, from 20.4 kHz to 1300 kHz and from 2.3 MHz to 40.5 MHz.

RSS
The investigations of the Radio Science Subsystem are based on the radio equipment which is also used for two-way communications between the Earth and Voyager. For example, the trajectory of the spacecraft can be measured accurately from the radio signals it transmits; analysis of the flight path as it passes near a planet or satellite makes it possible to determine the object's mass, density and shape. The radio signals are also studied at occultations for information about atmospheres, ionospheres, and ring particles.

Figure 5-5. Each Voyager spacecraft carries a science payload of 110 kg (240 lb) that uses 100 watts of power. Eleven investigations are designed to return complementary science across a broad spectrum.

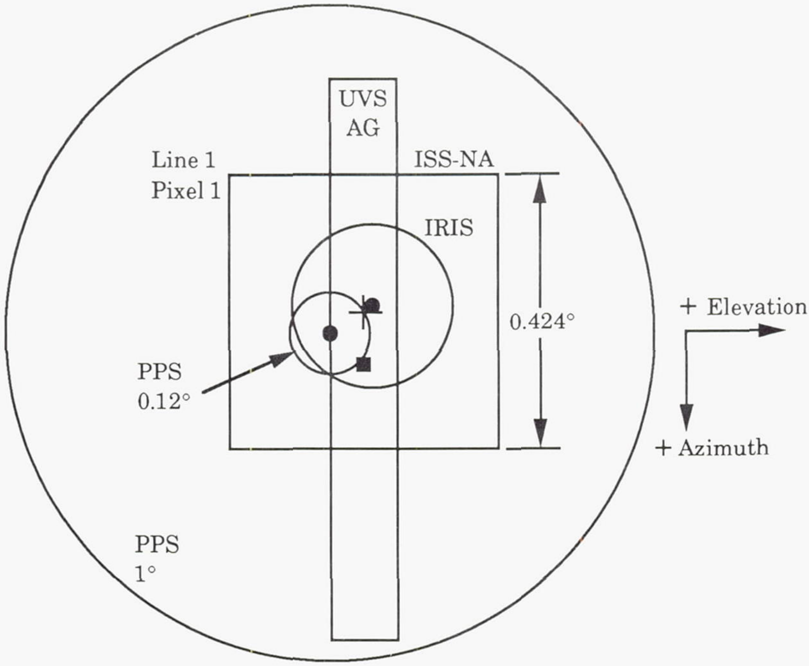
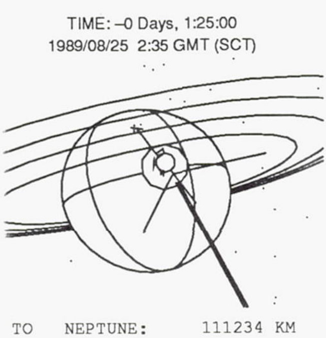


Figure 5-6. An attempt was made to align (for complementary science) the viewing axes of the scan platform optical instruments before launch, but slight misalignments of up to 0.1° were unavoidable when mounting fairly bulky instrument packages (Voyager 2 shown).

All matter in the universe above absolute zero temperature is undergoing some type of atomic (including molecular) motion. In fact, temperature is nothing more than the measure of the average amount of motion of a group of atoms or molecules. Matter that is hotter (higher in temperature) simply has faster-moving atoms or molecules.

When an atom or molecule absorbs or releases energy, it may do so only in certain ways. The central (and founding) idea of quantum mechanics is that matter may absorb or release energy only in "chunks" or quanta. This idea was conceived of and published by Max Planck in 1900. Five years later, Albert Einstein extended the idea by postulating that energy itself can only exist in quantized amounts, i.e., in integer multiples of some fundamental amount of energy. These two ideas form the intellectual starting point for quantum mechanics.



We have been loosely using the term "atomic motion," but we can see in Figure 5-7 that we must visualize three distinct types of motion. Molecules, consisting of two or more atoms, may rotate and

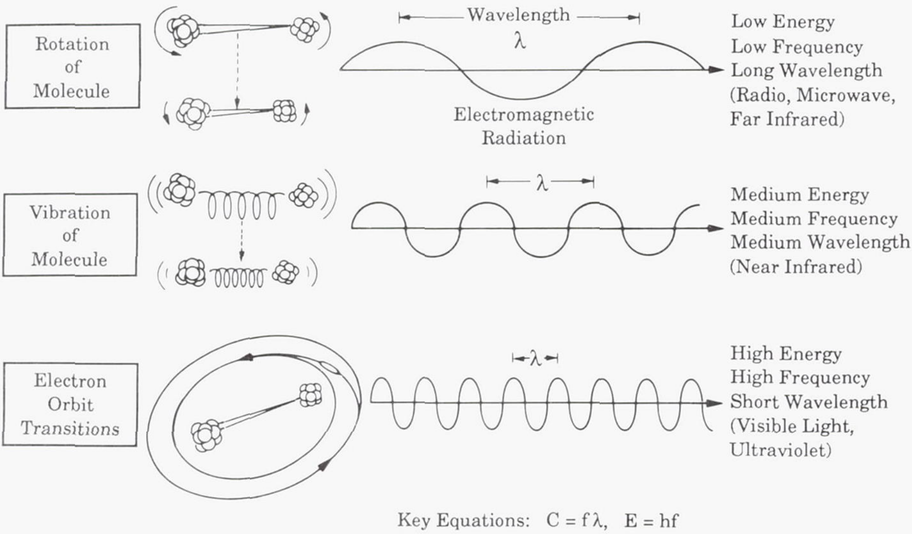


Figure 5-7. All matter above absolute zero temperature is constantly in motion, absorbing and re-emitting energy. Molecules, consisting of two or more atoms, can possess rotational and vibrational energy, as well as electron orbit transfers. Single atoms typically possess only the orbital transfers of electrons.

vibrate at different discrete energy levels. A molecule may absorb a specific quantum of energy, thereby moving to a higher energy state, or it may release a quantum of energy in the form of an electromagnetic wave. The lowest energy state changes are associated with changes in the rotational energy of the molecule.

Both molecules and individual atoms can undergo relatively large energy state changes whenever their "orbital" electrons jump between specific "orbits," again experiencing discrete energy-level changes characteristic of the particular molecule or atom in question. As shown in both Figures 5-7 and 5-8, these electron "orbit" transitions result in greater energy-state changes than those associated with changes in molecular rotation and vibration states.

Because each change in energy level is unique, a particular type of atom or molecule may be identified either when light (more generally, an electromagnetic wave) of a frequency it is known to emit is present, or when light of a frequency it is known to absorb is absent. The former is known as atomic or molecular emission. The latter is known as atomic or molecular absorption. Both techniques are used by the Voyager optical target body sensors to identify the presence of particular atoms and molecules.

The frequencies of light that a specific diatomic or polyatomic molecule can absorb or emit can be calculated. By determining, in advance, the atoms

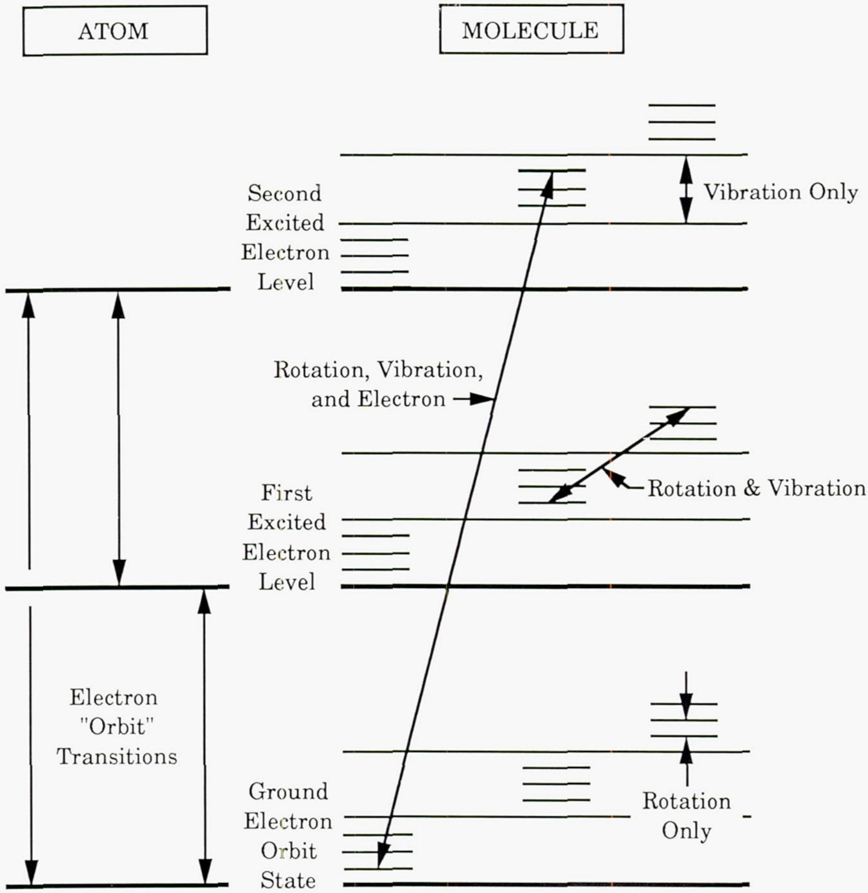
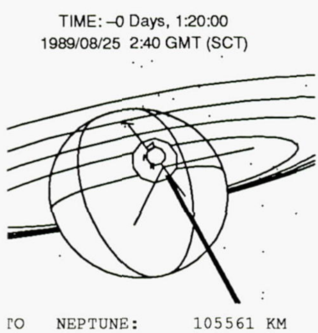


Figure 5-8. Molecules and atoms can only absorb and re-emit discrete packets of energy. The exact values of these energy level changes are unique to different molecules and atoms, acting like fingerprints to identify the matter in question.

and molecules that one wants to locate, one can determine the range of electromagnetic frequencies that must be detectable. Once the desired range of frequencies is known, one can design sensors that will indicate the presence of a particular atom or molecule.

Figure 5-9 shows both the range of wavelengths that the Voyager optical target body sensors can detect, and some of the atoms and molecules that emit or absorb energy within this wavelength range. One can see the large number of molecules potentially detectable by the IRIS; hence, the importance of preserving the health of the instrument for Neptune.



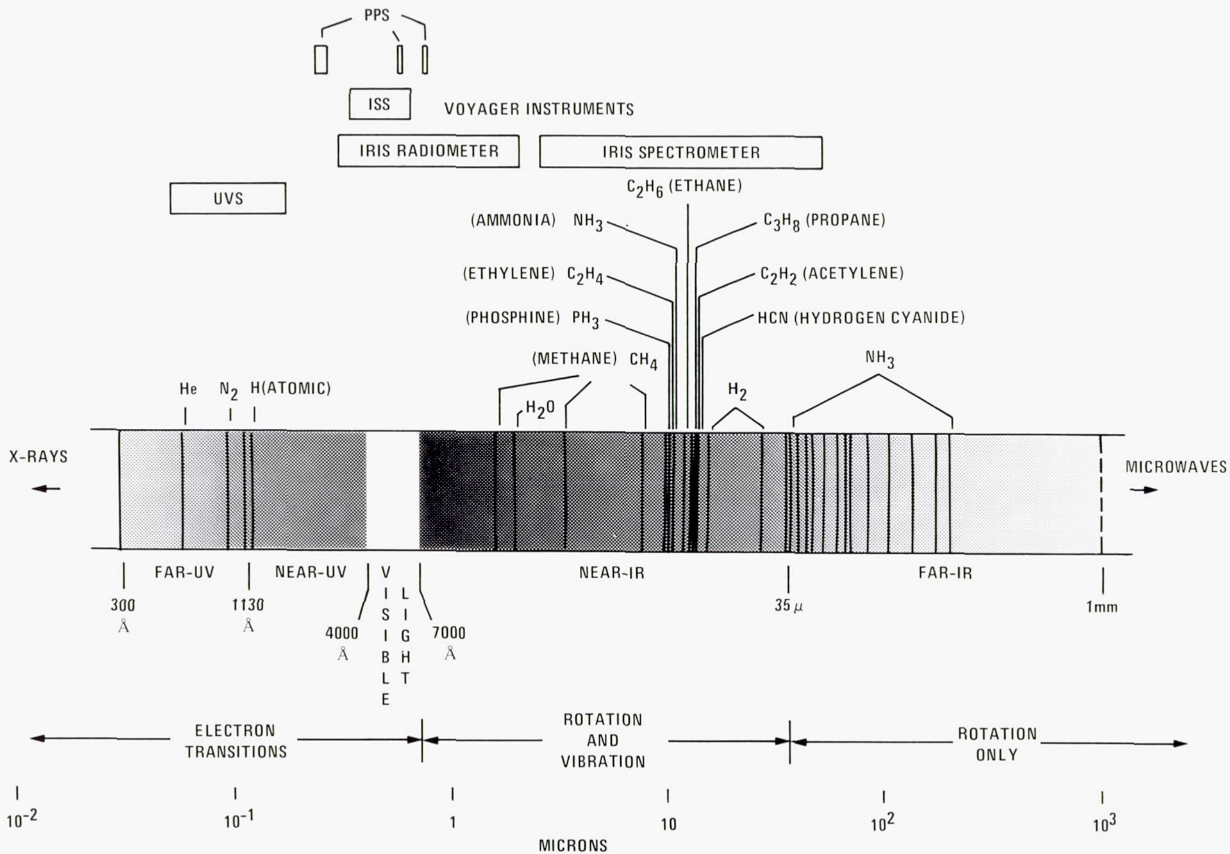
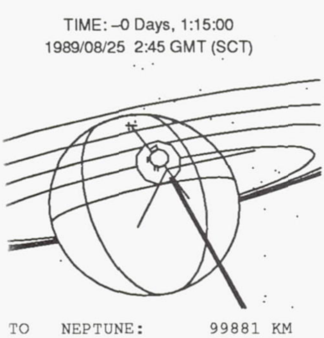


Figure 5-9. Voyager's optical instruments cover a large range of the electromagnetic spectrum, enabling the detection of many possible substances.

By now, you must be ready to dive into the Neptune encounter activities, having been briefed on the mission and science basics in Chapters 1 to 5. As the Guide will be published during the early portion of the Observatory Phase, we should hurry on to Chapter 6 in order to learn all about the exciting Neptune encounter plans and highlights.



Everything comes to those who can wait.

Francois Rabelais

6. ENCOUNTER HIGHLIGHTS

It's been nearly twelve years since Voyager 2 was sent on its Grand Tour of the outer solar system, and the last planet on the trip, Neptune, is just ahead. For the past three and one-half years, the bulk of the Voyager Project's efforts have been focused on planning and designing an extensive four-month, four-phase Neptune encounter—one which promises to be perhaps the most exciting of the Tour.

Table 6-1. The four phases of the Voyager-2 Neptune encounter activity span nearly four months. Most of the highest value science is taken during the NE phase.

Encounter Phase		Start and End Dates			Length	
Observatory	(OB)	Jun 05	to	Aug 06	62d	2h
Far Encounter	(FE)	Aug 06	to	Aug 24	18d	7h
Near Encounter	(NE)	Aug 24	to	Aug 29	5d	5h
Post Encounter	(PE)	Aug 29	to	Oct 02	33d	15h

Before we get into the detailed discussion of activities planned for the actual encounter period (see also Table 11-1), it would be helpful first to run through a brief orientation. Maintaining a mental image of where the action is happening and what's going on is key to understanding the encounter design. Once oriented, a description of what it takes to plan a visit like this—to a place our species has never been before—might help you form an appreciation for the behind-the-scenes work required to pull it off. It has been a first-rate challenge.

Getting Our Bearings

What little we know about this remote destination was summarized in Chapter 2. Chapters 3, 4, and 5 brought you a bit closer to the hearty Voyager spacecraft and the persevering people that got it to where it is now. But the solar system is a big place, and maybe you need a little help to see in your mind's eye where all of this is happening.

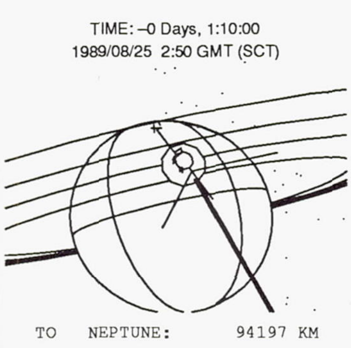
Just where *are* we going, anyway? Where *is* Neptune? Can someone *point* to Voyager 2? Let's think about these questions for a while and get our bearings. We've traveled far from home the past twelve years, so a check of the map might be a good idea about now.

Take another look at Figure 1-4, our "bird's eye view" of the solar system. Note first that, on the scale shown, the Earth is pretty close to the Sun. In fact, they're just a few degrees apart from Voyager's point of view. Now follow Voyager 2 on its Grand Tour path from Earth, past Jupiter, Saturn, and Uranus, and on to Neptune. Far from home, indeed! From Earth, Neptune is 4.5 billion km (2.8 billion mi) as the crow flies (or in this case, as the radio signal propagates). This is thirty times farther than the distance from the Earth to the Sun!

But that's not all: if Voyager 2 had an odometer on board, it would read nearly 7 billion km (nearly 4.4 billion mi) upon arrival at Neptune, since the more scenic Grand Tour route is longer than the straight-line distance. Our chosen path to Neptune is by no means the shortest way there, but it is the most practical path, which is what really counts in the space travel business. Chapter 7 explains this in detail.

Now let's get something else straight. How is Voyager 2 approaching Neptune? Refer to Figure 1-4 again, and note which way the planets circle the Sun. Voyager 2's path (trajectory) from Uranus to Neptune has been going away from the Sun, but not straight away: it has a moderate component in the same direction as Neptune's motion around the Sun as well. This trajectory does not actually aim Voyager 2 *for* Neptune's apparent location, but for where we believe Neptune will be at a precise time in late August; until that time, the planet will be shy of this aiming point, creeping slowly towards it every day. The most exciting part of the encounter is when this huge gaseous body gets buzzed by our tiny spacecraft when they meet at the aiming point.

The relative positions and velocities between Voyager and Neptune as they race to this aiming point create a useful viewing geometry. The spacecraft velocity component in the same direction as Neptune's orbital motion is nearly the same magnitude, too: 468,000 km/day, or 290,000 mi/day. These matched speeds keep either body from passing the other during most of the approach. In fact, the relative positions between the two are such that our spacecraft tends to stay close to the Sun-Neptune line, which gives its cameras and other sensors a nearly "full-moon" view of anything in the Neptunian system—the planet, Triton, Nereid, and other possible moons we haven't even discovered yet. (The reason we don't see a complete full-on view is because Voyager 2 is not exactly on the Sun-Neptune



line; a thin crescent of darkness shows on the right-hand side of the planet and moons as a result of this offset.) These high-illumination lighting conditions give us our brightest view of the objects there, and optimize our chances for discovering new moons long before Voyager visits them.

What about the other velocity component, heading essentially along (but not exactly on) the Sun-Neptune line? This component is over three times as fast as the other, and brings Voyager 2 closer to Neptune at the rate of 1.45 million km/day (900,000 mi/day). This speed would take Voyager from the Earth to the Moon in less than seven hours! At such a pace, it's no wonder Neptune gets visibly bigger day by day in the pictures beamed back during approach.

So, Voyager 2's approach to Neptune is easy to visualize if you just remember where you are standing. Stand at the aiming point, and both Voyager and Neptune will appear to be racing towards you on a collision course. Stand near Neptune, and Voyager will appear to be heading straight for you, coming right out of the Sun like an attacking fighter. Take our view from Earth, and you will see both bodies sweeping along at the same rate, with Voyager closing in on Neptune in a direction almost straight away from you.

Now you know how far away Voyager 2 is from us and generally how it is approaching Neptune. But *where* is Neptune? With Neptune's position known, one might guess (correctly) that Voyager 2 would be nearby. Given this, we can then impress our friends and actually point at our distant spacecraft. A visualization of the layout of the solar system will help us figure this one out.

The planets, the asteroids, and many comets lie approximately in the same plane as they orbit the Sun. Astronomers keep track of the small differences between these similar planes by referencing them to the orbit plane we're most familiar with: the Earth's. This plane is known as the ecliptic plane; in the context of Figure 1-4, it would be the sheet of paper it's printed on.

From our viewpoint on Earth's surface, these bodies (as well as the Sun) appear to rise at roughly the same place in the east (but at different times), traverse up into the sky along an arc, and set at about the same place in the west, again at different times. This track that the train of objects seems to be chugging along on is simply our edge-on view of the ecliptic plane, and their rise-and-set behavior we observe is caused by the turning of Earth on its axis. The planets, asteroids, and comets also move against the fixed starry background from night to night—moving through the signs of the Zodiac, as we say—but this motion is trivial compared to the rise and set motion.

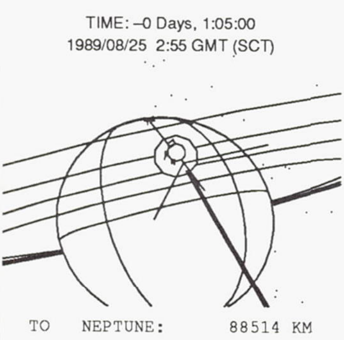
Now let's visualize where Voyager 2 is again. It started at Earth, visited Jupiter, Saturn, and Uranus, and is now relatively close to Neptune; all are residents of the ecliptic plane, including Voyager 2. We now have enough clues to figure out where to point our finger.

So where is our remote explorer? Step outside on a clear night and mentally draw the arc that passes through that day's sunrise and sunset points on the east and west horizons, respectively, and one or more of the visible planets (Mercury, Venus, Mars, Jupiter, or Saturn). This arc is the current edge-on view of the ecliptic plane. Then, on this arc, find—or have a friend that knows the stars help you find—the constellation Sagittarius, which appears near the eastern edge of the Milky Way. In that region of the sky Neptune is imperceptibly marching in its 165-year orbit from west to east along the ecliptic arc. Just a fraction of a degree more to the west, an aging, yet accomplished, spacecraft is closing in fast.

Not even the strongest telescope on Earth can see Voyager 2, but we know it's there, because we can hear it. And, after all these years, it can still hear us. In spite of the long wait, Voyager 2 is ready for Neptune, and so are we.

Aiming for Neptune

So . . . we're ready for a tour of the Neptunian system and our destination looms larger ahead day by day. Where do we want Voyager 2 to go, exactly? We don't get to pass through this distant place very often, and with so many tantalizing sights to train Voyager's sensors on, we would like it to be at all the right places at all the right times. Chapter 2 highlighted the interest in the large moon Triton. In addition to a close pass by Triton, we would also like Voyager to get close to Neptune and well into its magnetosphere, passing behind the planet if possible to ensure that the spacecraft's sensors and the Deep Space Network (DSN) antennas on Earth can take advantage of the high-value Earth and Sun occultation conditions that such a trajectory produces. Occultations by Triton would be great to have as well. A variety of views of the purported ring-arc system would also be welcome, with one or two bright star occultations if possible. But in our zest to gather all of this exciting science, we should not endanger our vulnerable spacecraft by placing it too close to the potential hazards posed by the ring-arc system, atmosphere, and radiation belts (see Chapter 8). In short, we are presented with a virtual smorgasbord of science, and we would like Voyager to gulp in as much as it (and we) can handle.



In this regard, Figure 6-1 is offered to whet your appetite. It shows the path Voyager 2 will take through the Neptunian system—one which satisfies nearly all of our science desires without taking on undue mission risk. (For reference, this view is close to what you would have if standing on the surface of far-away Nereid during the encounter.) Let's investigate why this trajectory was selected.

Although the success of this encounter depends on dozens of critical decisions, among the most important is the selection of the aiming point—exactly where in space and time Voyager 2 will come closest to Neptune. The aiming point sets up the geometry and timing for all encounter events, and thus controls most of the science-related parameters.

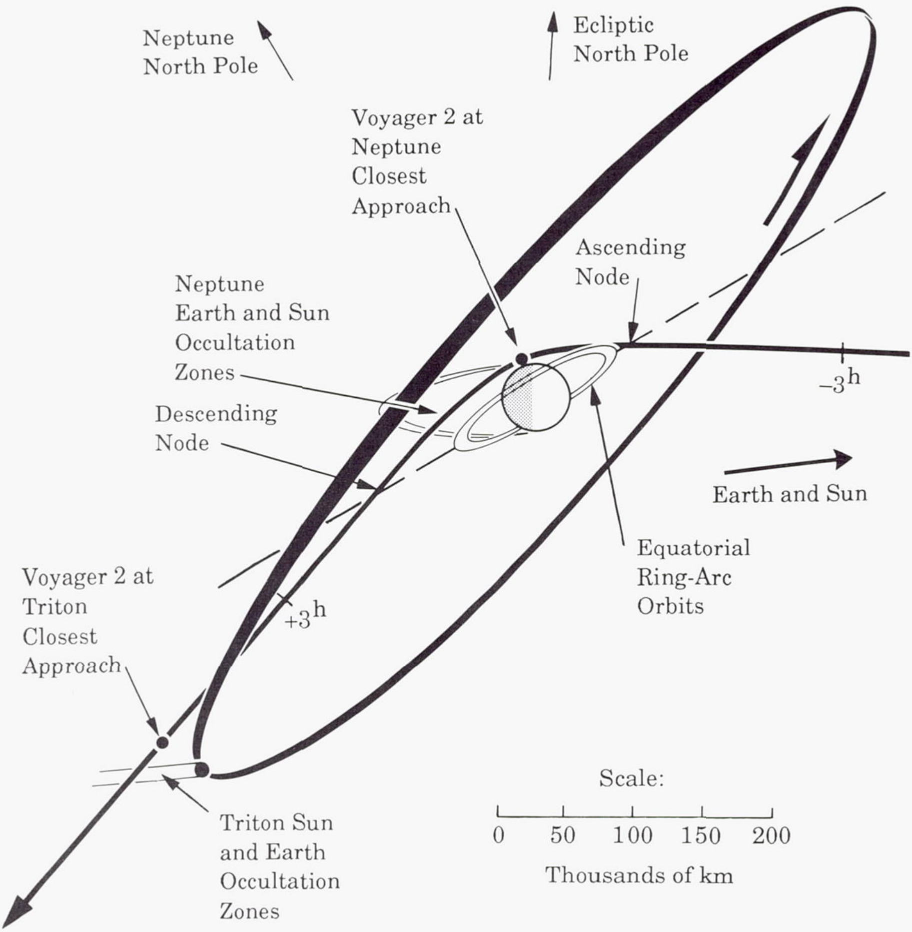


Figure 6-1. From this perspective, Neptune is coming at you out of the paper, and the Voyager-2 trajectory is in the plane of the paper. Note the position of Triton, and the gravitational bending of Voyager's trajectory required to reach it by diving closely over the northern polar regions of Neptune.

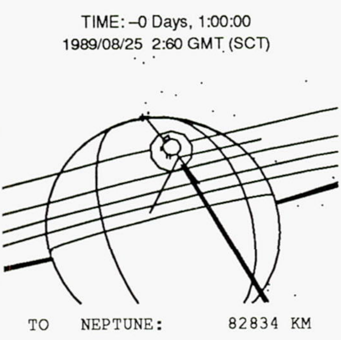
An added bonus (and complication) at Neptune is that, for the first time on the Grand Tour, we are free to target Voyager 2 to any reasonable aiming point. At Jupiter, Saturn and Uranus, we had to worry about getting to the next planet, so rigid "swingby corridor" aiming-point constraints were imposed to comply with the Grand Tour trajectory design requirements. These constraints simplified the aiming-point selection process, and served their purpose well; they are chiefly responsible for guiding Voyager to Neptune.

Incidentally, you may be wondering why we don't send Voyager 2 towards Pluto after the Neptune encounter. After all, we have never been there, and being so close now, it seems to be a waste not to give it a try. It turns out that there is an aiming point at Neptune that could gravity-assist Voyager to Pluto, but there's a *big* problem with it: it requires such a close pass by Neptune that the spacecraft would actually have to go deep into the planet itself! Clearly, this option is not practical. Pluto will have to wait.

Thus, here we are, with a multitude of aiming points from which to choose. Among these possibilities, might one class satisfy our desires more than the others? After much study and analysis, the scientists and encounter designers have concluded that the answer to this question is yes, for several reasons.

The aiming point selection process for Neptune proved to be an arduous task, and was certainly one of the most challenging of all the Voyager encounters, including those for Voyager 1. A discussion of the detailed steps of this process is beyond the scope of this Guide, so only the highlights of this eight-year exercise (1980-1988) will be treated here.

To visualize the aiming-point possibilities that were considered in 1980 (before Voyager 2 had even arrived at Saturn!), imagine a scene where a huge sheet of thin paper thousands of kilometers on a side is placed perpendicular to the line connecting Voyager and Neptune on the spacecraft's post-Uranus trajectory, like a huge billboard between the two. (Recall that from Neptune's point of view, Voyager is heading straight for it, and thus straight for this billboard.) Think of this sheet as a big target that the Voyager navigators want to shoot the spacecraft through, using Voyager's maneuvering capability. Shoot Voyager through a different spot on the sheet, and you get a different set of encounter conditions (geometry and timing) at Neptune. Figure 6-2 shows what we would want to draw on this target to help the Navigation Team with their shot.



The circular region of aiming points on our target leads to a collision with Neptune, so we certainly don't want to shoot anywhere in there. This holds even for point P, which would send us on to Pluto . . . but for the fact that we cannot shrink Neptune's mass to a point to allow the math to be realized. At the far right side of Figure 6-2, near the point labeled N_1, a line of aiming points results in a collision with Triton, as does a small arc of points in the northern polar area of the planet. Targeting just to the side of either arc would give us an arbitrarily close pass by Triton, with the possibility of Earth and Sun occultations by Triton in some cases. The Earth and Sun occultations by Neptune are a bit easier to get: the acceptable aiming points map into a broad region across the target (mostly because Neptune is so big).

If we really want that close pass by Triton, we have to make a choice. A point near N_1 passes far from Neptune; this choice satisfies Triton and Neptune occultation science objectives and safety concerns, but compromises other Neptune science investigations that would work better if done closer to the planet. In contrast, close-in aiming points in Neptune's northern polar region satisfy all major science objectives (including Triton occultations), but introduce some concerns about environmental hazards.

Intermediate aiming points such as that labeled N_2 are also available if one wants to sit on the fence and be safe about everything, but the result is a dull encounter—Voyager wouldn't get very close to Neptune or Triton.

To make the first part of a very long story short, the northern polar region, near the "inner Triton locus," was judged in 1980 as the most

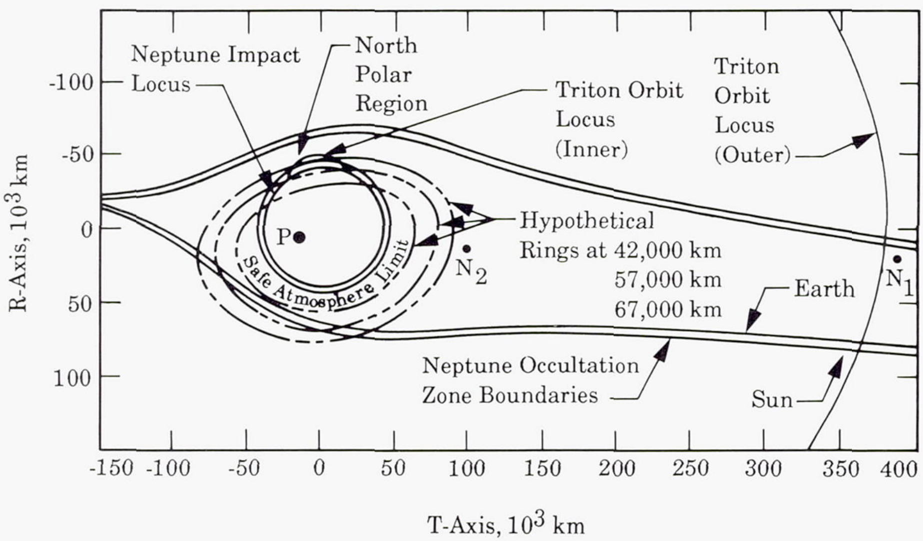


Figure 6-2. Our giant target between Voyager 2 and Neptune is shown here, marked with the Neptune aiming-point possibilities that were studied over eight years ago.

desirable place to pass by Neptune. (The ring arcs, incidentally, weren't discovered until late 1980, after this original aiming point had been selected!) This region requires a close pass over the northern polar region of Neptune to gain sufficient gravitational deflection (see Figure 6-1) for a close encounter with Triton five hours later. Properly executed, such a trajectory could please nearly all members of the Voyager science, engineering, and management communities. After considerable study, an original aiming point resulting in a 44,000 km (27,300 mi) Triton miss distance was chosen, with an associated Neptune arrival time (closest approach) of 23:12 Greenwich Mean Time (GMT) on August 24, 1989.

As Neptune encounter planning progressed after this original aiming point was selected, the Voyager Imaging Team saw the need for a closer Triton pass to reduce the level of smear in the Triton images. (A closer pass causes the spacecraft to take a more direct, head-on approach to Triton, reducing the cross-wise motion of the moon in Voyager's cameras.) In addition, the Radio Science Team asked for a slightly later arrival time to bring Voyager 2 higher above Australia's horizon (by virtue of Earth's rotation) for the important Earth occultation experiments at Neptune and Triton.

These requests were approved in the fall of 1985, leading to a new Triton miss distance of 10,000 km (6200 mi) and a Neptune closest approach time of 04:00 GMT on August 25. This new trajectory was judged to be the best for science, while still keeping outside the environmental hazard zones, including the newly discovered ring arcs.

Then, in late 1985, the estimates for four separate parameters describing the Neptunian system were updated based on the latest available knowledge, and all four changes caused an *increased* environmental concern. In fact, the nominal aiming point appeared—on paper—to send the spacecraft straight through the postulated ring-arc system and dangerously close to the atmosphere! The Project was sent into high gear reevaluating the encounter design, and the trajectory had to be moved out. By late 1986, a new aiming point was baselined that retained the 04:00 Neptune arrival time, but moved the Triton miss distance out to 40,000 km (25,000 mi).

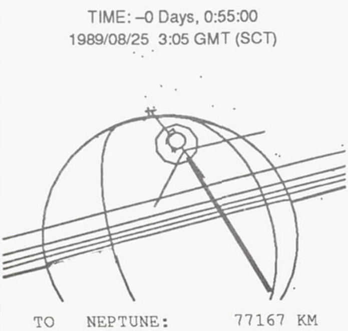


Figure 6-3 zooms in on Neptune's northern polar region from Figure 6-2 and depicts our present aiming space. The latest physical models of the Neptunian system suggest that the "40K Triton" aiming point is safe with at least 95 percent confidence, probably more. Voyager 2 is expected to pass about 5000 km (3100 mi) outside the hazard thresh-

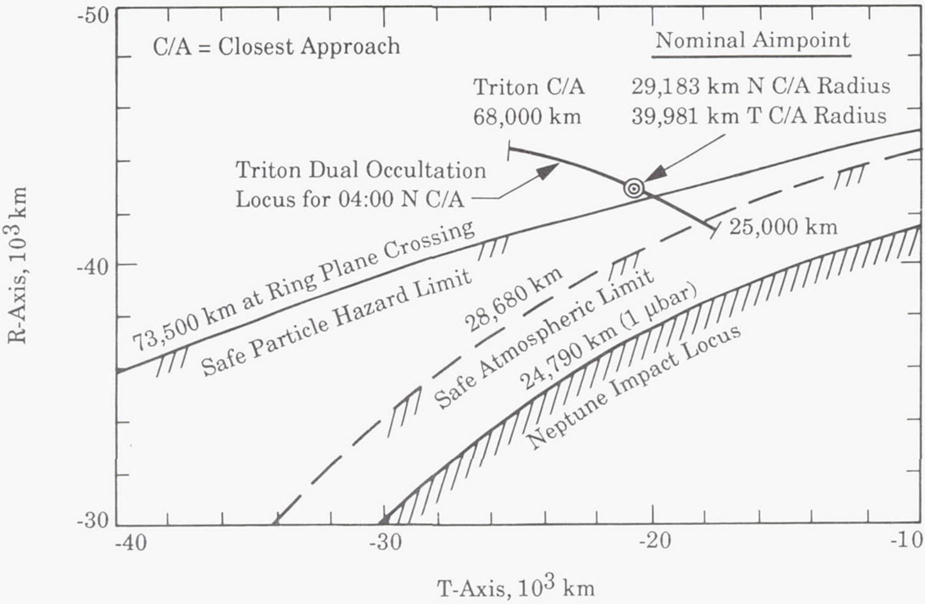


Figure 6-3. The northern polar aiming space at Neptune satisfies all major science objectives, but introduces some environmental hazard zones to be given safe clearance.

olds for both the ring-arc system and atmosphere, and will probably be exposed to measurable—yet tolerable—levels of radiation as it transits Neptune's magnetosphere. Chapter 8 describes in more detail what was done in the encounter sequence design to deal with Neptune's environmental hazards. Later discussion in this chapter will fill you in on more of the actual encounter events and scenes.

Setting Up for the Encounter

Skimming Voyager 2 over Neptune to get it close to Triton raises another concern that has received considerable attention over the past two years or so: navigation. There are lots of uncertainties at Neptune, such as its exact position and size: ditto for Triton. Plus, we never know exactly where Voyager 2 is at a given time, much less where it will be months in the future. (Actually, considering how far away this is happening, we know these values fairly well, but still not well enough to do a *perfect* job.) All of these uncertainties pile up to make navigating through Neptune's domain a formidable task.

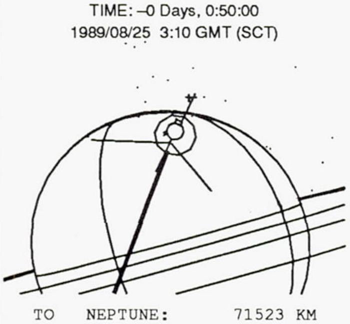
For example, although the selected trajectory promises to give us a tour we'll never forget, it's still very sensitive to aiming-point changes. This is especially true for the Triton science, because relatively small position errors at Neptune closest approach tend to get magnified by the gravitational bending effect, leading to errors nine times bigger by the time Voyager 2 arrives at Triton. Arrival-time errors also get magnified. This means that good navigation—good shooting at our aiming space target—is a must for this encounter.

How big is this spot we're aiming for? Considering how far away it is from Earth, it is unbelievably small to most people. The skilled Voyager navigators will try to guide Voyager through an imaginary needle's eye about 100 km (62 mi) wide, while the spacecraft is going a blistering 27 km/sec (nearly 61,000 mi/h)—and they expect to predict when this will happen to within *one* second! Threading this needle at Neptune closest approach—just above its cloudtops—will ensure with about 85 percent confidence that Voyager 2 passes through the Earth and Sun dual-occultation zone behind Triton 5 hours and 43 minutes later. (We would like to achieve a 90 to 95 percent probability of success for this dual occultation, but 85 percent is about the best we can do, given the uncertainties.)

So how does one become a good shooter? One way is to take several shots. For a number of reasons, Voyager 2 is nudged to the nominal aiming point over several years with a series of Trajectory Correction Maneuvers (TCMs), rather than one big maneuver just before Neptune. The general strategy has been to ease Voyager down to the desired aiming point from a safer one farther out from the planet, away from the hazard zones. As we learn more and more about the Neptunian system during Voyager's approach, these maneuvers become more refined and precise, homing in on the desired aiming point with more confidence. One such TCM was executed in early 1987, and another in late 1988. TCM B17C (described below) was just completed in April this year. Three more are planned during the encounter period as well.

Striving for Perfection

In Chapter 3, you were introduced to the concept of Computer Command Subsystem (CCS) loads, the computer programs stored on board Voyager to control its activities. At any given time, one of these programs must be running, or the spacecraft will cruise along doing nothing. For the Neptune encounter, ten CCS loads have been designed to execute the desired sequence of events. One additional load is ready to support a contingency option also. The contents of each CCS load will be described later in this chapter, but now is a good time to introduce you to their names.



Every Voyager-2 CCS load, except the contingency load, starts with the letter "B"; Voyager-1 loads start with "A". The OB phase is composed of three loads: B901, B902, and B903. The FE phase has three as well: B921, B922, and B923. NE has only two, B951 and B952. B951 is the load that includes the closest approaches to Neptune and Triton, and is very complex compared to the others. The encounter ends with two loads in the PE phase, B971 and B972. The sole contingency load for the Neptune encounter is called R951, for reasons explained in Chapter 8; it backs up the high-value B951 load. To keep Voyager-1 cruise activities to a minimum during the Voyager-2 Neptune encounter period, a very long CCS load known as A818 will keep Voyager 1 going from just after the start of OB until more than two months after PE has ended.

Completing these loads and getting them "on the shelf," as we say, was no easy task. In fact, it took about two years of preparatory work (1984-1985), and over three years of intense activity (1986-1989) by nearly all facets of the Voyager Project to do it, with assistance from many other individuals sprinkled around the globe. Even though they are on the shelf, these loads are not the best we can do, so even while you read this Guide, they are being updated.

The encounter CCS load development process essentially got started in February 1984, when a three-day workshop was sponsored in Pasadena by the Voyager Project to establish a scientific framework within which to plan the Voyager Uranus and Neptune encounters. Regular meetings of the Voyager Science Working Groups (SWGs) in 1984 and 1985 refined the Project's understanding of the Neptune system and the important scientific issues that could be addressed effectively by Voyager once it arrived. By the Uranus encounter, a preliminary version of the first month or so of the Neptune encounter (essentially the OB phase) had already been developed, but further work had to be put on the back burner to concentrate on Uranus.

Following the highly successful Uranus encounter in early 1986, everyone got busy on the Neptune CCS loads; the work has been non-stop since then. Constructing high-fidelity timelines of the desired encounter sequence of events proceeded by encounter phase—not in chronological order, but saving the most difficult designs for last (OB, PE, FE, and NE).

This design process consisted of five phases: Guidelines Development, Scoping, Integrated Timeline, Final Timeline, and Uplink Product. By the end of the Uplink Product phase, each CCS load is supposed to be mature enough to actually work on board Voyager, but perhaps not optimally. The last load to finish this phase was put on the shelf in April this year—over three years after the process got a serious start!

But we want these computer programs to be perfect, remember? To approach this goal, each load is then taken "off the shelf" (chronologically this time) and run through another step in this grueling process called the Updates phase. Each load is updated with the latest geometric and timing knowledge, and sometimes subjected to a few minor sequence modifications to correct errors discovered, to eke out a bit more science, or to perform something more efficiently or safely. The first load of the encounter (B901) started this phase in March this year, and was done just before it was sent to the spacecraft in early June. Each subsequent load follows this example.

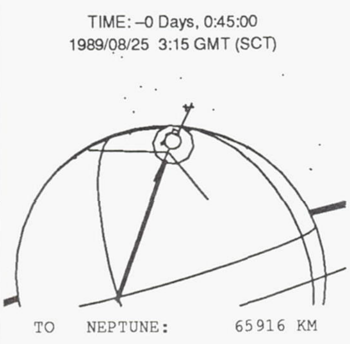
There is more to say about this Updates phase, because we're not done yet! Now the real fun begins.

Critical Late Activities

The geometric and timing updates that each load receives before it is uplinked are called a Late Ephemeris Update, or LEU. To do one of these, updated estimates of Neptune system physical constants (body sizes, masses, locations, etc.) and the latest description of Voyager's trajectory are fed into a fancy computer program that calculates all of the changes necessary in a given CCS load to re-center its observations and reset the various timing relationships between activities. Feed these updates and the "outdated" CCS load to the computer, and out comes a more nearly perfect load—just in time to send it to our distant recipient. This is good enough for most loads, but not *all* of them! There's more . . .

Imagine you are heading for Neptune, riding along with Voyager 2. For months and months, the planet just seems to hang there in front of you, growing in size, but not very fast. The view is almost boring, it's so constant. Then, in the last month or so, you get closer and closer, and the detail starts popping out at you. Fairly suddenly, you note sizes and positional relationships with unprecedented clarity and accuracy. Pictures are taken that can be used to pin down the orbits of the planet and moons. You see things never seen before. In short, in just a few weeks, all of the uncertainties you had been struggling with for *years* begin to shrink down to a mere fraction of their prior values. The Neptunian system comes alive for the first time ever, and models transform into reality.

This situation is going to happen in late July and all through August, and a plan is needed to deal with all of these late improvements in our knowledge. For the CCS loads that orchestrate Voyager's activities close to Neptune, special updates will be needed to factor in the most current data at the latest possible



time—so late, in fact, that these updates must be sent to Voyager *after* the CCS load has already started executing! Reliance on the LEU alone simply is not good enough, because the most sensitive observations would fail if attempted without the latest information, and critical maneuvers to fine-tune the aiming point could miss the planned target by more than the sequences could tolerate.

Two special update techniques are invoked to make these critical updates. To update selected observations, a procedure similar to the LEU, called the Late Stored Update or LSU, is used. For putting some "English" on the TCMs, a TCM "tweak" is done.

LSUs will be required for two loads: B951 and B971. One is needed for B951 because it controls activities closest to the planet, where the effects of the various uncertainties are most evident. The B971 load demands an LSU because we won't know—until it happens—exactly at what angle Voyager 2 will be leaving Neptune after its gravity-assist slingshot over the northern polar region, and several high-value observations in B971 are sensitive to this angle. Predicting this outbound trajectory beforehand is beyond our capabilities, so we'll tell Voyager what it is—once we can pin it down—with an LSU.

The TCM tweak technique will be used in B903 for TCM B18, in B922 for TCM B19, and in B923 for TCM B20. For TCM B19 and TCM B20, a tweak option even exists to make Voyager 2 do a last-minute trajectory "bailout" maneuver, to avoid any environmental hazard surprise discovered during the last few days before Neptune closest approach.

Developing the sequence of events for all of these late updates—the Late Activity Timeline—required a considerable effort by most of the Voyager teams. The process started in early 1987 and, after a great deal of study and analysis, by mid-1988 a reasonable timeline for the LEUs, CCS load uplinks, LSUs, and TCM tweaks had been worked out. The busiest part of these "late activities," as they are called, is shown in Figure 6-4. Figure 6-5 breaks down a typical late activities block into its component steps.

For most of August, the late activities will be keeping many encounter teams busy around-the-clock. The Navigation Team will gather data from Voyager 2 to improve their mathematical models of the Neptunian system and Voyager's orbit; the scientists will evaluate these new models and recommend changes to the various parameters that control their observations; maneuver designers will request minor changes to the TCM designs; spacecraft and sequencing experts will push each CCS load through a series of computer programs to incorporate these changes and check for errors; operations people will grease the skids to make sure the updates are sent to

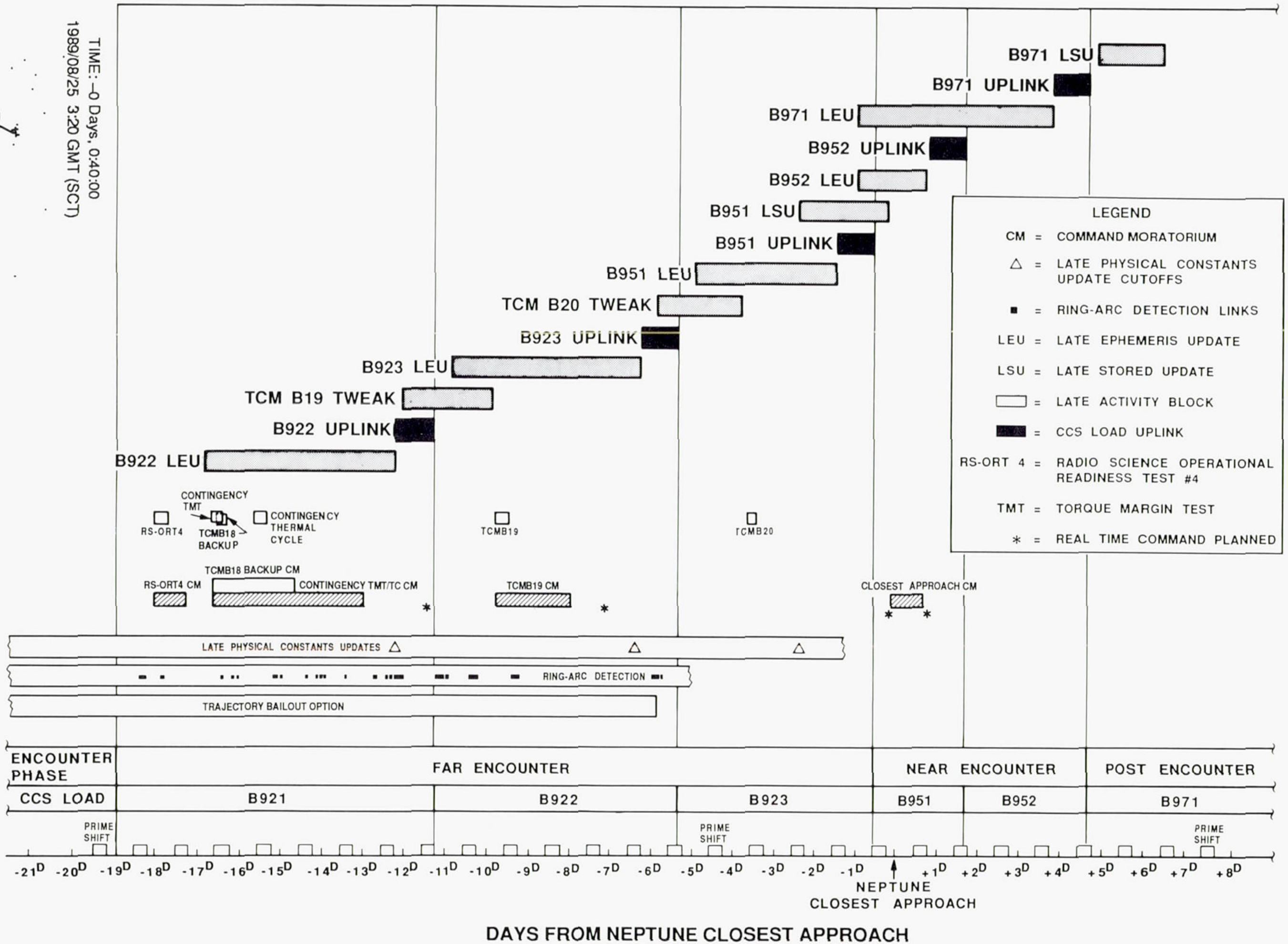


Figure 6-4. Neptune Encounter Late Activity Timeline.

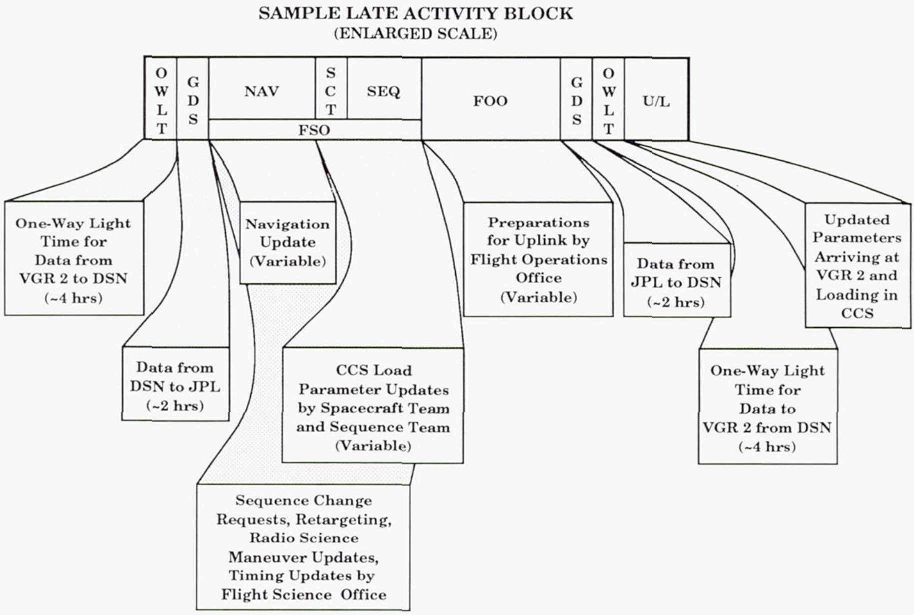


Figure 6-5. The Voyager encounter teams will work around-the-clock in a fast-paced effort to incorporate the latest knowledge about Neptune's system into the CCS loads, using a series of activity blocks like this one.

the spacecraft on time; and mission management will be hosting meeting after meeting to approve the change requests and maintain coordination.

If we pull off the late activities as planned—and we are confident we shall—Voyager 2 will execute CCS loads that are as perfect as its keepers on Earth can supply.

Practice Helps to Make Perfect, Too

After the preliminary Late Activities Timeline had been developed in mid-1988, a new phase in encounter preparations began: Test and Training. As the name implies, this activity is concerned with testing some of the clever ideas planned for Neptune (see Chapter 9) and conducting some rehearsals of the more complex periods of the encounter (including the LEUs and LSUs), so we don't try everything "cold turkey."

This work began essentially one year before the start of the encounter, and ended virtually at the start of B901, in June 1989. It, too, required a major effort by nearly all Voyager encounter teams. Refining all of the preliminary notions of the various encounter activities into final, precise descriptions that satisfy everyone—and then checking them all out—was by no means a simple job.

The Test and Training phase was a mixed bag of activity, involving nearly all Project teams and the generation of lots of detailed plans and procedures for every team to follow during the various exercises. Since October 1987, a series of Operational Readiness Tests (ORTs) has been conducted to validate and calibrate the Earth-based communications network to be used for gathering the important radio science occultation data coming from Voyager 2 as it passes behind Neptune and Triton. These "RS-ORTs" continue well into the encounter. Special Capability Demonstration Tests (CDTs) were conducted on Voyager 1 (our "testbed") and Voyager 2 in 1988 and early 1989 to verify new spacecraft operating techniques and to gather some performance calibration data. One of these CDTs completed in April with Voyager 2 served a dual purpose: it validated the roll-turn TCM concept planned for use with TCM B20 (see Chapter 9), and in the process performed another TCM, called TCM B17C.

As a final dress-rehearsal for the encounter, a high-fidelity Near Encounter Test (NET) was executed in May on board Voyager 2. It simulated the most complex chunk of the B951 sequence, with everyone on Earth playing their appropriate roles. Now, it's time for the real thing.

How the Bits Flow

To maintain its busy schedule of activities, Voyager 2 requires periodic bursts of instructions from Earth. Various teams at JPL, in turn, demand near-daily infusions of Voyager engineering and science data and ground-computed navigation data to help them keep track of what is happening at its distant locale. In Chapter 3 you were introduced to the system that facilitates this flow of information: the Ground Data System (GDS).

As the excitement of the encounter builds, more and more images and data plots will be displayed on TV monitors at JPL only minutes after the raw information required to display them arrives at Earth from Voyager 2. The casual observer may think that the spacecraft is beaming everything we see on the TV monitors directly to JPL, much like a cable TV satellite does when it transmits a newly released movie or popular sporting event to the local distribution station or even individual homes. But in the case of Voyager 2, this is simply not what happens; the digital data bits must first zip around a fair part of the globe via the GDS before they reach JPL and those eagerly awaiting their arrival.

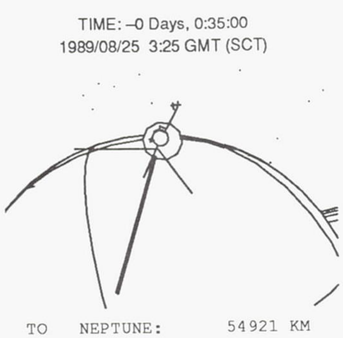


Figure 6-6 shows the telecommunications "highway" for the first part of this journey — after the data travel over 4.4 billion km from Voyager to Earth, that

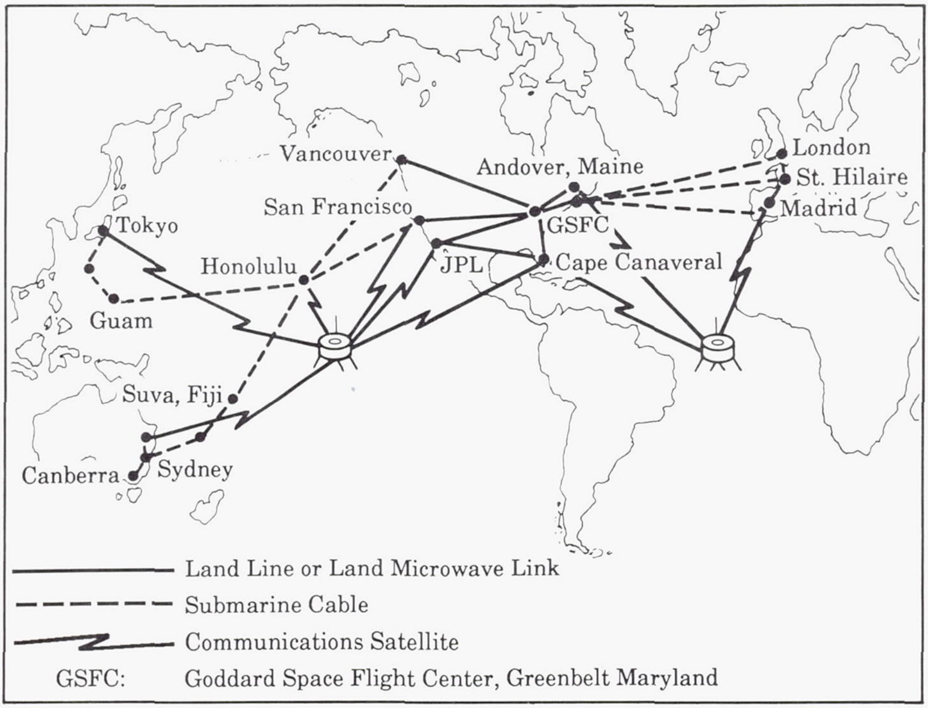


Figure 6-6. Land-based telephone lines, land-based microwave links, submarine cables and communications satellite links are all fair choices for constructing possible data paths with the GCF; ultimately, availability, reliability, and cost dictate which route is best.

is! From one or more antennas at the DSN sites (California, Australia, or Spain), the data bits (including navigation data) are routed to JPL by one of many possible routes arranged ahead of time by NASCOM telecommunications network personnel based at NASA's Goddard Spaceflight Center in Greenbelt, Maryland. The NASCOM people employ a world-wide switching and routing system called the Ground Communications Facility (GCF) to get their job done.

For the Neptune encounter, two special cases for routing Voyager data arise. The signals from the Very Large Array in New Mexico are sent via satellite link to the Goldstone, California, DSN site, where they are combined (arrayed) with Goldstone's signals; the product is then relayed to JPL via the GCF. At Usuda, Japan, the radio science occultation signals are recorded as they are received, and tapes of the recorded data are then sent directly to JPL for further combining with the comparable signals that arrived via the GCF from Australia. This combining takes place days after Neptune closest approach, since shipping tapes by conventional mail is much slower than electronic transfer of data.

Data arriving at JPL via the GCF are first manipulated in the Mission Control and Computing Center (MCCC), in particular the third floor of Building 230 (see Figure 6-7). Note that commands to Voyager leave the MCCC, pass through the GCF, and get transmitted to the spacecraft by the appropriate DSN antenna.

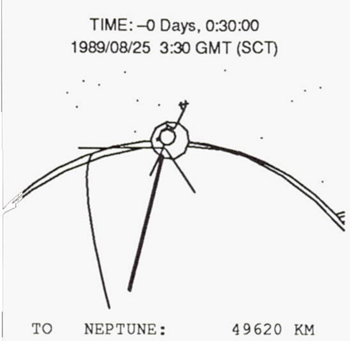
The MCCC is where the data are decoded and identified for future use by the Data Capture and Staging (DACS). After passing through the DACS, the data are sent to the Test and Telemetry Subsystem (TTS) for display, to the Data Records Subsystem (DRS) for archiving and storage, and to the Multimission Image Processing Subsystem (MIPS), where some of the initial image processing is done. From the MCCC, the data are routed in various specialized formats to several sites on Lab, as depicted in Figure 6-7. Processing of these data streams is done in real time and non-real time, depending on the data type and ultimate use.

Science data of all types are sent to the second floor of Building 230, where many Voyager Principal Investigators and their staffs will be stationed. Radio science data are routed to the third floor of Building 264, where a special program called RODAN deconvolves the signals into scientifically meaningful numbers. An array of science support workstations on the second floor of Building 301 (known as VNESSA, the Voyager Neptune Encounter Science Support Activity) and on the third floor of Building 264 (known as VISA, the Voyager Imaging Science Activity) also receive their own data feeds, as do additional MIPS computers in Buildings 168 and 169. Optical navigation (OPNAV) images are processed on the second floor of Building 264 using dedicated computers and specialized software. And, last but not least, von Karman Auditorium is connected to most of the other sites to ensure that encounter surprises are displayed and routed to the thousands on Lab and millions off Lab who anxiously wait to see them.

Neptune at Last!

All of the discussion above was included in this chapter to get you oriented and sensitized to the enormous effort required to plan for this encounter. It hasn't been easy. What we have to show for the past three and one-half years is ten nearly perfect CCS loads and an incredible amount of planning and preparation. The reward for everyone's hard work will be the show that Voyager 2 sends back from Neptune.

With this appreciation, sit back now and relax. It's time for the final stop on Voyager's Grand Tour of the outer solar system . . . and here we go!



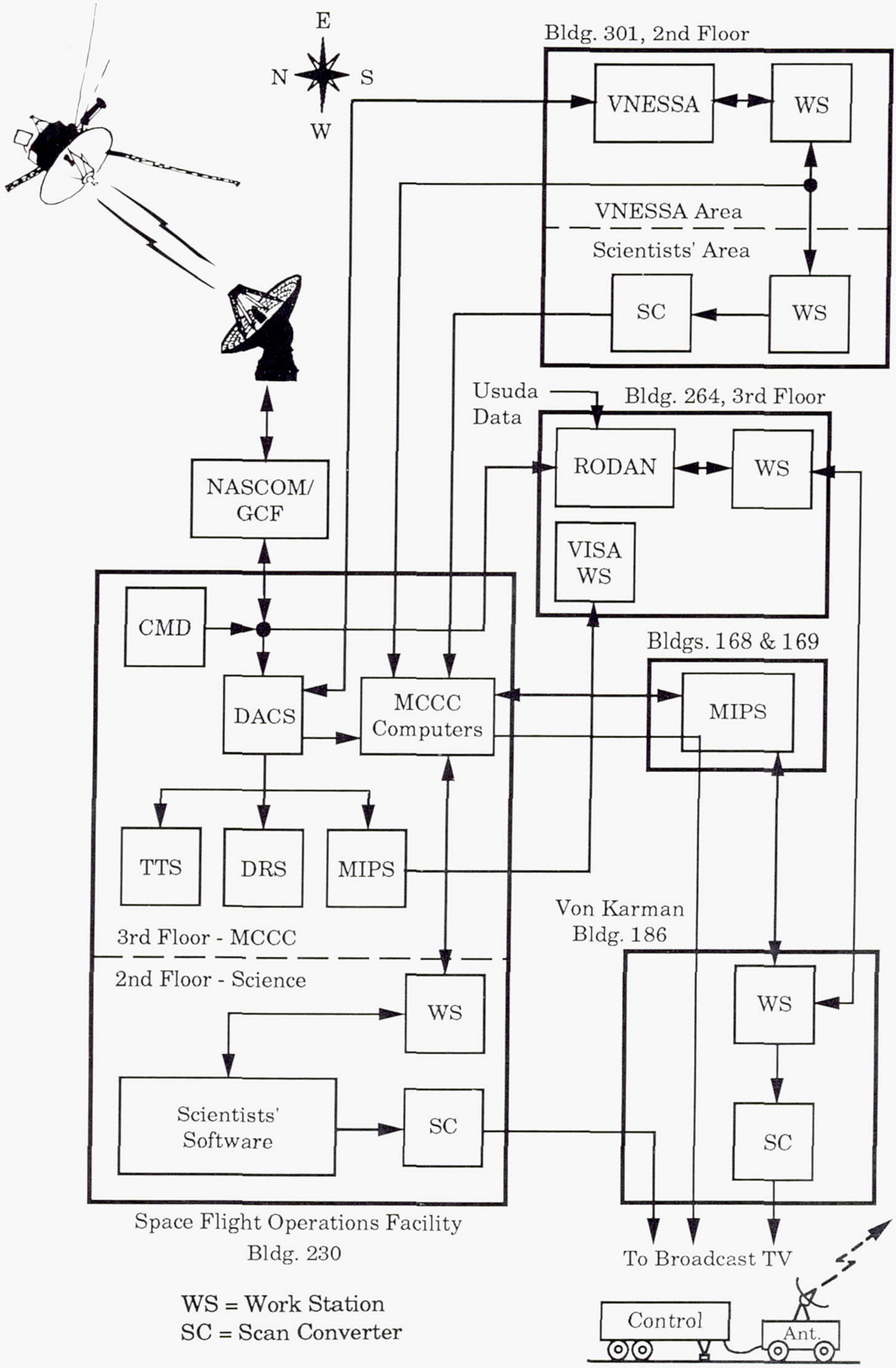


Figure 6-7. Data bits can travel down a number of possible paths before they arrive at their final destinations. The MCCC at JPL serves as the central switchboard for most data arriving at the Lab.

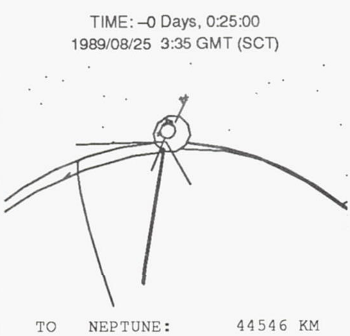
Observatory Phase (OB)

The name of this phase describes its primary nature well: it is a repetitive two-month watch of the Neptunian system, which to some will seem almost monotonous. For most of those on Voyager just finishing the hectic Test and Training phase, the relatively slow-paced OB events will come as a refreshing break (although updates of subsequent loads will prevent much relaxation); the teams staffing the DSN sites are notable exceptions to this trend, however, since their workload actually increases at the start of this phase. Figure 6-8 highlights the last month of Uranus-to-Neptune cruise activities and all of those in OB. Note that OB starts with a fairly active load, which is followed by a relatively inactive load twice as long, and ends with a short, relatively active load.

The first OB CCS load, B901, starts at 80 days, 21 hours, and 17.6 minutes before Neptune closest approach (N-80d 21h 17.6m, for short), and ends exactly 18 days later. (Refer to Table 6-2 for a listing of the start times and durations of all ten encounter loads.) Two hours into the load, the first of many executions of a link called VPZOOM gets underway. (Refer to the end of Chapter 2 for a summary of how these science links are named.) Each VPZOOM is designed to take five Imaging Science Subsystem (ISS) narrow-angle (NA) camera pictures of Neptune every one-fifth of a planetary rotation (one-fifth of a Neptunian "day"). By stringing together all of the VPZOOM frames taken during the same times of day, five movies will be made to highlight the visible atmospheric features marching across Neptune's disk. Scientists can then use these movies to estimate the velocities and dynamics of the various cloud features and bands—some of which have been observed for several months now, though not very clearly. A link similar in emphasis to VPZOOM, called VPMOVIL, is especially tailored to bring out faint details in Neptune's atmosphere.

Shortly after VPZOOM starts, surveys of Neptune with the Ultraviolet Spectrometer (UVS) also begin, using the USSCAN, USMOSAIC, and UPAURORA links, among others. USSCAN looks for signatures of neutral hydrogen and excited ions in a one-dimensional scan across the entire Neptunian system (out to beyond Triton's orbit), while USMOSAIC does the same in a two-dimensional array. UPAURORA dwells on Neptune only, looking for signs of auroral discharges near the planet's south pole. These broad surveys continue for all of OB.

Bursts of Planetary Radio Astronomy (PRA) and Plasma Wave Subsystem (PWS) data are taken once per day throughout OB as well; the frequency of the



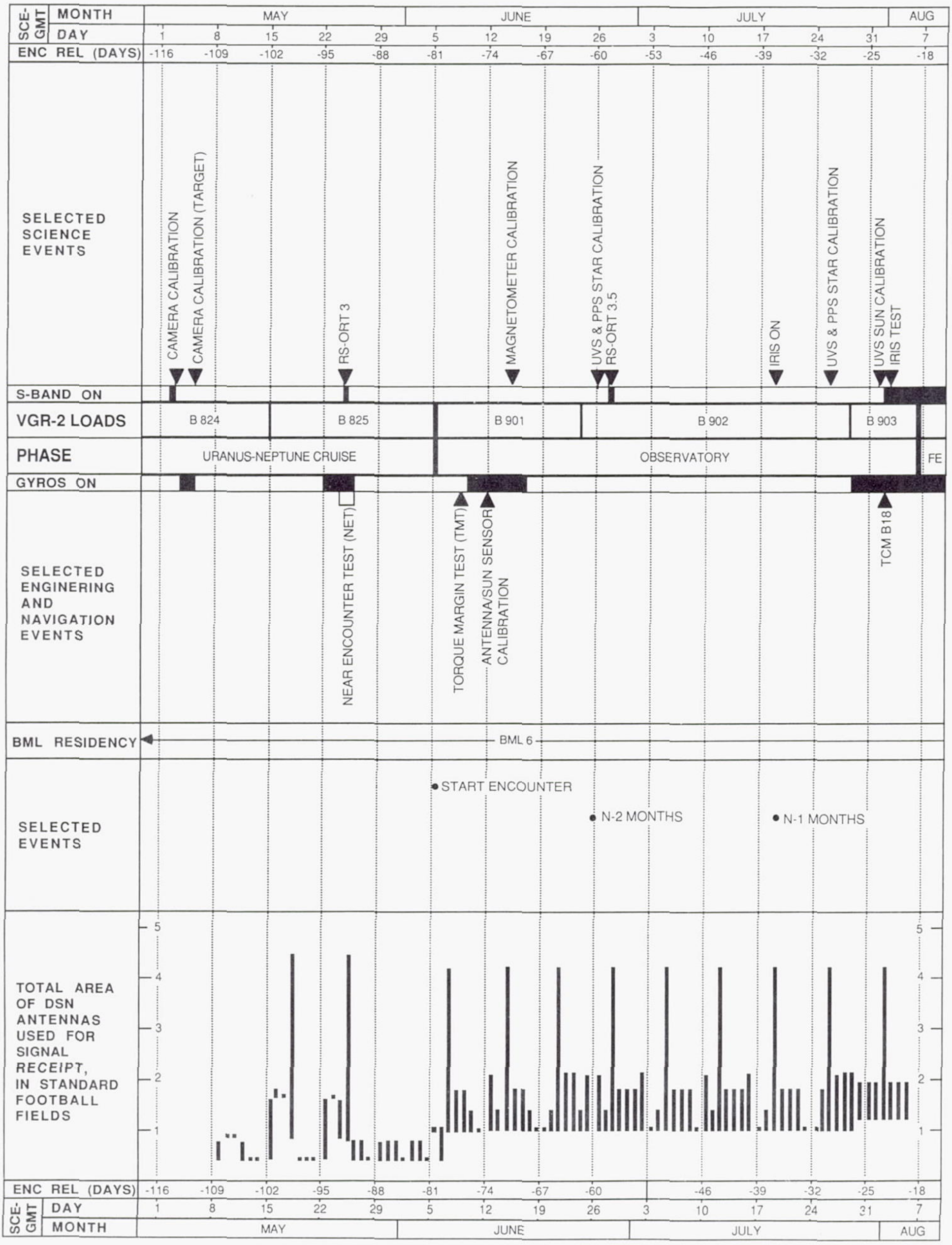


Figure 6-8. Voyager-2 Neptune encounter overview timeline for late Uranus-to-Neptune cruise and the Observatory phase.

Table 6-2. Ten CCS loads will be used during the four-month Neptune encounter.

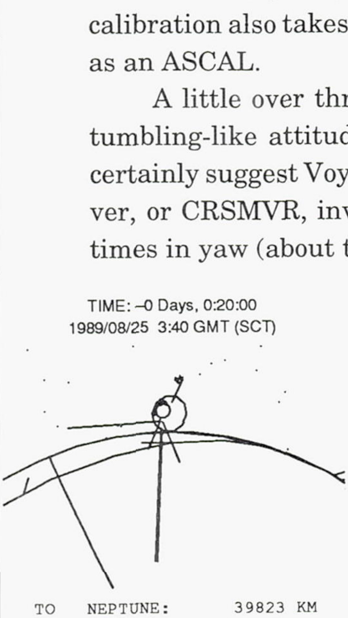
Enc. Phase	CCS Load	Start Time (GMT-SCET)	Start Time (Enc. Relative)	Load Duration
OB	B901	06:42, Jun 05, Mon	-80d 21h	18d 00h
	B902	06:42, Jun 23, Fri	-62d 21h	34d 22h
	B903	04:42, Jul 28, Fri	-27d 23h	9d 04h
FE	B921	08:42, Aug 06, Sun	-18d 19h	7d 14h
	B922	22:42, Aug 13, Sun	-11d 05h	5d 23h
	B923	21:42, Aug 19, Sat	-05d 06h	4d 18h
NE	B951	15:42, Aug 24, Thu	-00d 12h	2d 05h
	B952	20:42, Aug 26, Sat	+01d 17h	3d 00h
PE	B971	20:42, Aug 29, Tue	+04d 17h	12d 23h
	B972	19:42, Sep 11, Mon	+17d 16h	20d 16h
Post-Neptune Cruise	B001	11:42, Oct 02, Mon	+38d 08h	6 weeks

PRA signal in particular will likely be the best indicator of Neptune's core rotation rate.

Three days into B901, the last scheduled scan platform Torque Margin Test (TMT) is performed (refer to Chapter 9). This one-hour test measures friction levels in the azimuth (Az) and elevation (El) actuators.

One day after the TMT, the spacecraft gyroscopes (gyros for short) are turned on to support about two and one-half weeks of calibration-related activities. First among these, at about N-73d 15h, is a calibration of the High Gain Antenna (HGA) signal pattern and a Sun sensor alignment check. This calibration also takes about one hour to complete; you may see it referred to as an ASCAL.

A little over three days after the ASCAL, the spacecraft executes a tumbling-like attitude maneuver that to the uninitiated observer would certainly suggest Voyager 2 was out of control. This Cruise Science Maneuver, or CRSMVR, involves cartwheeling the spacecraft end-over-end four times in yaw (about the Y axis) and four times in roll (about the Z axis) to sweep the magnetometer (MAG) sensors on their long boom through the interplanetary magnetic field in order to determine where "zero" is, and also to measure the local magnetic field generated by the spacecraft itself. Voyager has been doing this calibration for years now, so it is not as tricky as it seems at first.



Right after the CRSMVR, the gyros are turned off and Voyager initiates a routine that determines the orientation of the MAG boom itself—in bending and twisting—within two degrees. The remainder of B901 (another week) includes more of the repetitive observations already described.

At roughly N-63d 20h, the transmission of CCS load B902 begins arriving at the spacecraft, having been sent some 3h 58m earlier from Earth. A little less than one day later, B901 clocks out and lets B902 take control of Voyager's activities.

B902 continues with the systems-level observations started in B901, and also includes calibrations of the UVS and Photopolarimetry Subsystem (PPS) instruments. Between N-60d 2h and N-59d 15h, these instruments are pointed at various stars to get baseline data for later comparison to similar data to be taken during the Neptune, Triton, and ring-arc system occultations in B951 and post-Neptune calibrations in PE.

Between N-58d and N-57d, RS-ORT 3.5 is conducted; it is a scaled-down version of RS-ORT 3, performed in conjunction with the NET in May. This ORT exercises the Neptune-Earth occultation sequence in B951 with the extensive DSN arrays on Earth, including the Usuda site in Japan, a newcomer for this encounter. For the first time in the encounter, the S-band transmitter will be turned on during this test, but only for a few hours.

If there is to be such a thing as a lull during the encounter, the month following RS-ORT 3.5 has to be it. Between about N-57d and N-28d, our untiring explorer executes—what else?—a continuous stream of Neptune system scans. The only significant exceptions to this routine are the turn-on and checkout of the Infrared Interferometer Spectrometer and Radiometer Subsystem (IRIS) at N-38d and another PPS/UVS star calibration at N-31d, just before the end of B902. Weekly Very Large Array (VLA) passes are scheduled into the DSN coverage as well. (The VLA is also supporting Voyager for the first time this encounter.)

B903 starts at N-28d with a command to turn the Voyager gyros on; they remain on until almost the end of the encounter. After a CCS timing test three days into the load, the tweak for the first encounter trajectory maneuver, TCM B18, is uplinked from Earth. Since a bit more data are returned during this last week of OB, a little extra DSN coverage is planned, as one can see in Figure 6-8.

It hasn't been mentioned until now, but all during OB (and since TCM B17C in April), Voyager has been beaming back a fairly steady stream of optical navigation images (OPNAVs) of Neptune, Triton, and Nereid to help navigators on Earth determine where everything is in the Neptunian system, and where Voyager 2 is heading. Anything new learned along the way is factored into the TCM B18 tweak. By N-24d 3h, the tweak parameters are loaded in the CCS in time for TCM start at N-23d 16h.

TCM B18 is designed to remove all known errors—aiming-point position errors and arrival-time errors—from the Voyager trajectory. At just shy of a month from Neptune, we still don't know exactly how far off we are from the desired aiming point, but we know a lot more than we did at TCM B17C last April!

To ensure the total electrical power usage onboard Voyager does not exceed allowable limits during the TCM, the radio transmitters are reconfigured from X-band high power/S-band off (X-HI/S-OFF) to X-band low power/S-band low power (X-LO/S-LO) just before the TCM starts. Once the maneuver has executed, the system goes to X-HI/S-LO, and stays that way until the next ORT in early FE. The X-LO/S-LO configuration is used during TCM B19 as well.

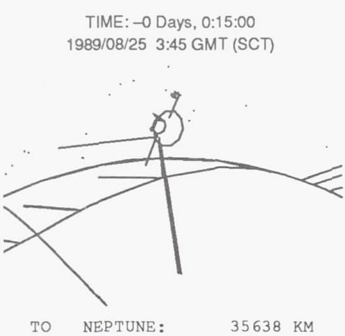
The TCM involves significant power state changes on the spacecraft as well as attitude changes; both of these influences alter Voyager's thermal state significantly, and thus induce a relatively long command moratorium of three days (refer to Chapter 4). While everyone on Earth is waiting for the command moratorium to end, Voyager executes a UVS Sun calibration at N-23d 10h, checks the IRIS health, and resumes its Neptune system scans. For the first time in the encounter, a concerted effort to detect very small satellites begins at N-21d 1h, using the VSATSRCH link. Movies of the ring-arc region are radioed back on a daily basis as well, in hopes of seeing some evidence for material there at this early date.

Commandability returns near the end of OB at about N-20d, just in time to uplink the first FE load, B921.

Far-Encounter Phase (FE)

At the start of the encounter, Neptune was over 11 weeks away, and its disk and ring-arc system, combined, only spanned one-sixth of the NA camera field of view. Now, at N-18d 19h, Neptune's disk alone captures about one-quarter of this view, and things look much more interesting. The end of this phase leaves Voyager 2 as on-target as it will ever be, and only twelve hours from Neptune closest approach.

As you can see in Figure 6-9, the first of the three FE CCS loads is the longest, but still only a half-day longer than a week; the other two clock out in less than a week. Needless to say, these shorter durations are indicative of a higher level of activity than we saw in OB. More activity means more things for Voyager



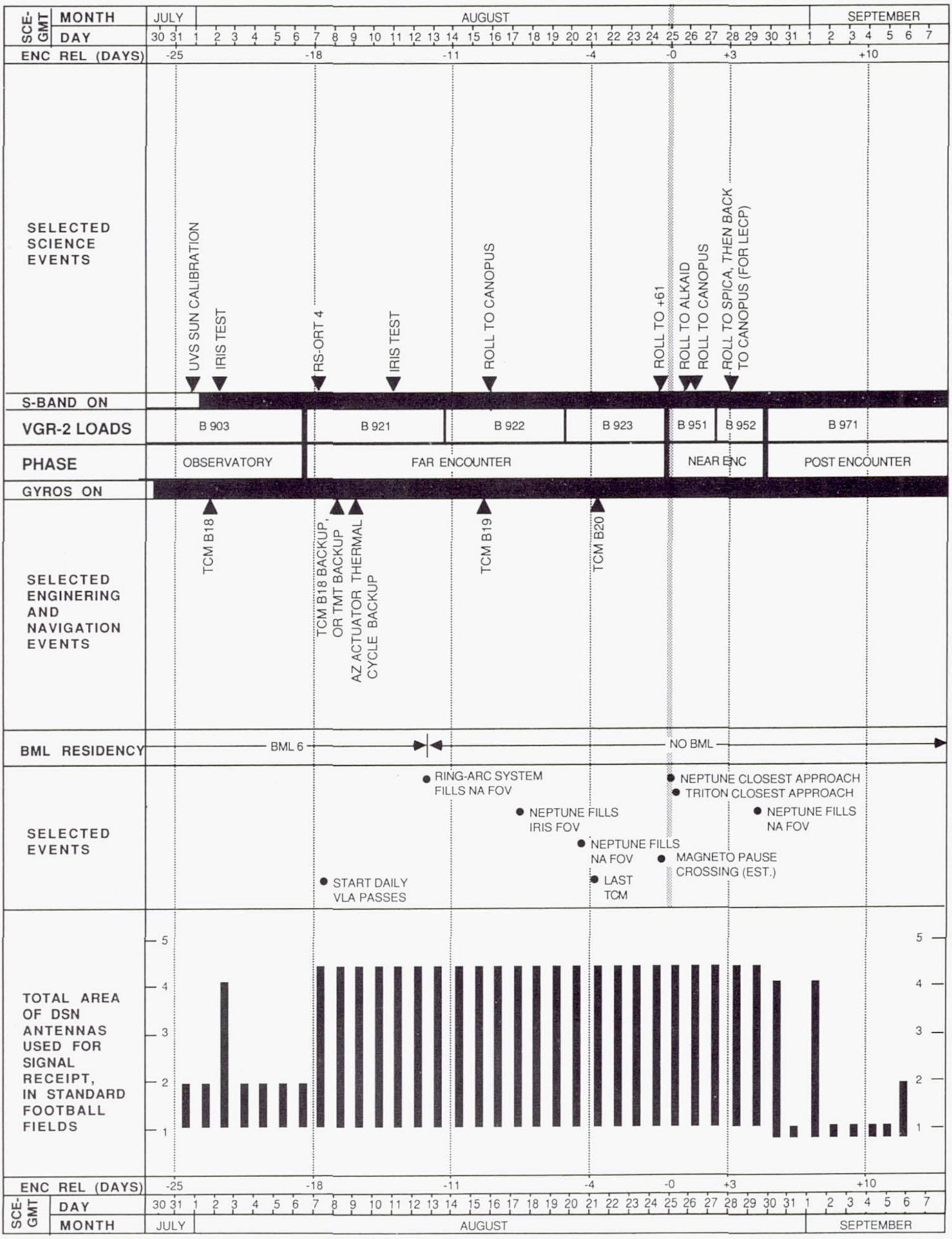


Figure 6-9. Voyager-2 Neptune encounter overview timeline for Far-Encounter and Near-Encounter phases.

to do, and more CCS words required to do them. In active periods, the CCS just can't control things for long before its memory space is used up.

More activity also means more telemetry data, so the DSN kicks into high gear at the start of B921 with daily VLA passes in addition to the amount of arraying used in late OB. The FE phase also marks the start of the busiest series of late activities, depicted in Figure 6-4.

B921 starts with an intensive series of system scans, much like OB, only more. The UPAURORA links are executed four or more times per day, as are a variation of VPMOVIL, called VPNAMOVI, which focuses on the large-scale features in Neptune's atmosphere. The VSATSRCH links and probing of the ring-arc system continues, and more links train the sensors on Triton as well. The PRA and PWS data bursts are beamed back to Earth twice per day.

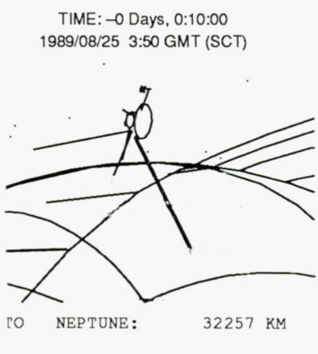
Starting less than one day into B921, the last full-scale dress rehearsal for the encounter, RS-ORT 4, is conducted. The test involves lots of Voyager and DSN people worldwide, and lasts about ten hours. Anticipation mounts.

Uplinking the parameters for either a backup TCM B18 or contingency TMT (should either be needed; see Chapter 8) is scheduled for N-17d 3h, just after the command moratorium caused by RS-ORT 4 ends, and eight hours in advance of the planned start time for the contingency sequence.

At N-16d 9h, the Navigation Team takes all optical and radio data returned from Voyager up to this time and starts solving for the latest Voyager-2 trajectory. With this solution in hand, the detailed design for the next planned maneuver, TCM B19, proceeds. (The data cutoff for the TCM B19 tweak occurs at N-12d; the maneuver itself executes at N-9d 18h.)

At N-13d 13h, another IRIS health check is performed in preparation for the high-value RPDISK observation scheduled in B922. Through the end of the B921 load, most of the pre-encounter instrument and spacecraft calibrations are finished, and all of Voyager's sensors are kept busy observing Neptune, Triton, Nereid, and the ring-arc system. Included in the returned data stream are various optical and radio data-types needed to support the upcoming all-important TCMs, B19 and B20.

And the view is getting better: at N-12d, the ring-arc system fills the entire NA field of view.



In the six-day B922 load, which starts at N-11d 5h, more and more details appear for the first time. Faced with so many science opportunities, more CCS memory would be welcome. To accommodate this need, the sixth version of the Backup Mission Load

(BML 6) is removed from the CCS late in B921 to free up much-needed memory space.

At this time, the Navigation Team is working quickly to solve for the TCM B19 tweak values. By now, the uncertainties that everyone fussed over for so many years are dropping precipitously, thanks to Voyager. Neptune's position is now known three times more accurately than just two weeks earlier; Triton three to six times better, depending on the component. Time of arrival is one-third better. The value of Triton's radius is no longer a mystery. And by this time, the mass of Neptune is known three times better than at the start of FE, because the subtle tug of the planet's gravity can already be detected in Voyager's radio data. Our explorer is accelerating . . .

The TCM B19 tweak is uplinked to Voyager 2 at N-10d 9h, and 15 hours later the maneuver executes. This TCM is designed to remove all estimated trajectory position errors, but only some of the estimated time-of-arrival error. The movable blocks in B951 (more on these later) take care of the residual timing offset. The Navigation Team estimates that there is about a 25 percent chance that TCM B19 will not be needed, given that TCM B20 remains to remove some position errors.

Immediately following TCM B19, Voyager performs a turn about its roll axis (Z axis) to acquire a different lock star for its star tracker. This change from Achernar to Canopus places the onboard fields and particles instruments in a better position for measuring magnetospheric properties during the days before Neptune closest approach.

The RPDISK observation in B922 from N-9d to N-7d is the highest-value science observation in the FE phase; the matching outbound observation in PE is equally important. Why? Because one of the most meaningful measurements to get for planets (especially the gaseous ones) is the heat balance—the difference between how much heat a planet receives from the Sun and how much it gives off. Knowing this, we can deduce things about the body's interior, and unlock some of the secrets hidden by its clouds. At around N-7d 12h, Neptune's disk should just barely fill the IRIS field of view; this is the optimum time to make the heat balance measurement. (Neptune fills a bit over one-half of the NA camera view at this time; Triton is still very small.)

One day after the RPDISK observation, at N-6d, the uplink for the final FE load starts. About 18 hours later, this load, B923, takes control of Voyager 2. Neptune looms ahead, almost filling the entire NA camera field of view.

B923 is sequenced with specialized observations of Neptune and its atmospheric features, its ring-arc system, Triton, and Nereid. All eleven

Voyager investigations are employed. There are even some images reserved for moons we didn't know existed at the start of the encounter—but suspected they would be found. Fields and particles instruments continue their search for Neptune's magnetosphere. The unambiguous sign of Voyager's entry into this strange domain of whistlers, chirpers, and electromagnetic static and hissing is the magnetopause crossing, estimated to occur between about 27 and 9 hours before Neptune closest approach.

In parallel with Voyager's heightened activity, the activities in and around JPL quicken, as the various Voyager teams prepare for Neptune and Triton closest approach, and as the rest of the world takes a serious and public interest in what is happening far away at Neptune.

The late activities schedule really picks up during B923. The TCM B20 tweak, B951 LEU, B951 LSU, B951 uplink, B952 LEU, and B971 LEU keep most of the support teams busy night and day. The Navigation Team works especially hard to pin down all of the values needed to support the critical TCM B20 tweak design and B951 LEU and LSU updates.

The final aiming point for the encounter is fixed when TCM B20 starts executing at N-3d 16h 51m. This special roll-turn TCM is designed to adjust Voyager's position such that the probability of it hitting the desired aiming point in Triton's dual-occultation zone is maximized. After TCM B20, no further TCMs are planned—ever—for Voyager 2. Its fate is thus transferred to the final slingshot over Neptune's northern polar region and the meager forces it may encounter in interplanetary and interstellar space.

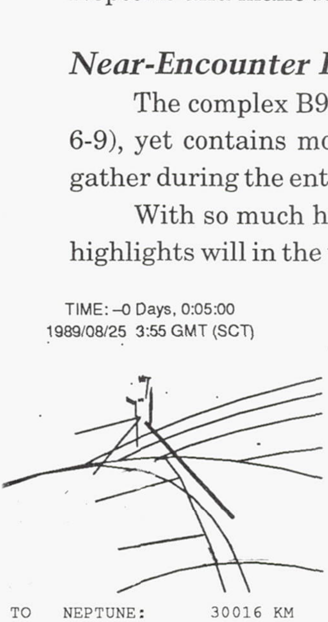
In less than five days from its start, B923 clocks out and hands over Voyager operations to B951. FE is over, and Voyager is ready to buzz Neptune and make its close pass by Triton.

Near-Encounter Phase (NE)

The complex B951 load lasts only two days and five hours (see Figure 6-9), yet contains most of the high-value science we expect Voyager 2 to gather during the entire four-month encounter. It stands in a class by itself.

With so much happening in this load and its companion, B952, these highlights will in the truest sense be highlights, because it would require an entire lengthy chapter to describe all of the activities in detail. Briefly, then, here is the NE phase.

We pick up Voyager at N-12h 17m 36s, speeding towards its nominal aiming point at about 61,000 km/h (37,700 mi/h), only 1 percent faster than its steady-state Uranus-to-Neptune cruise value. Neptune is still tugging, but not very hard . . . yet.



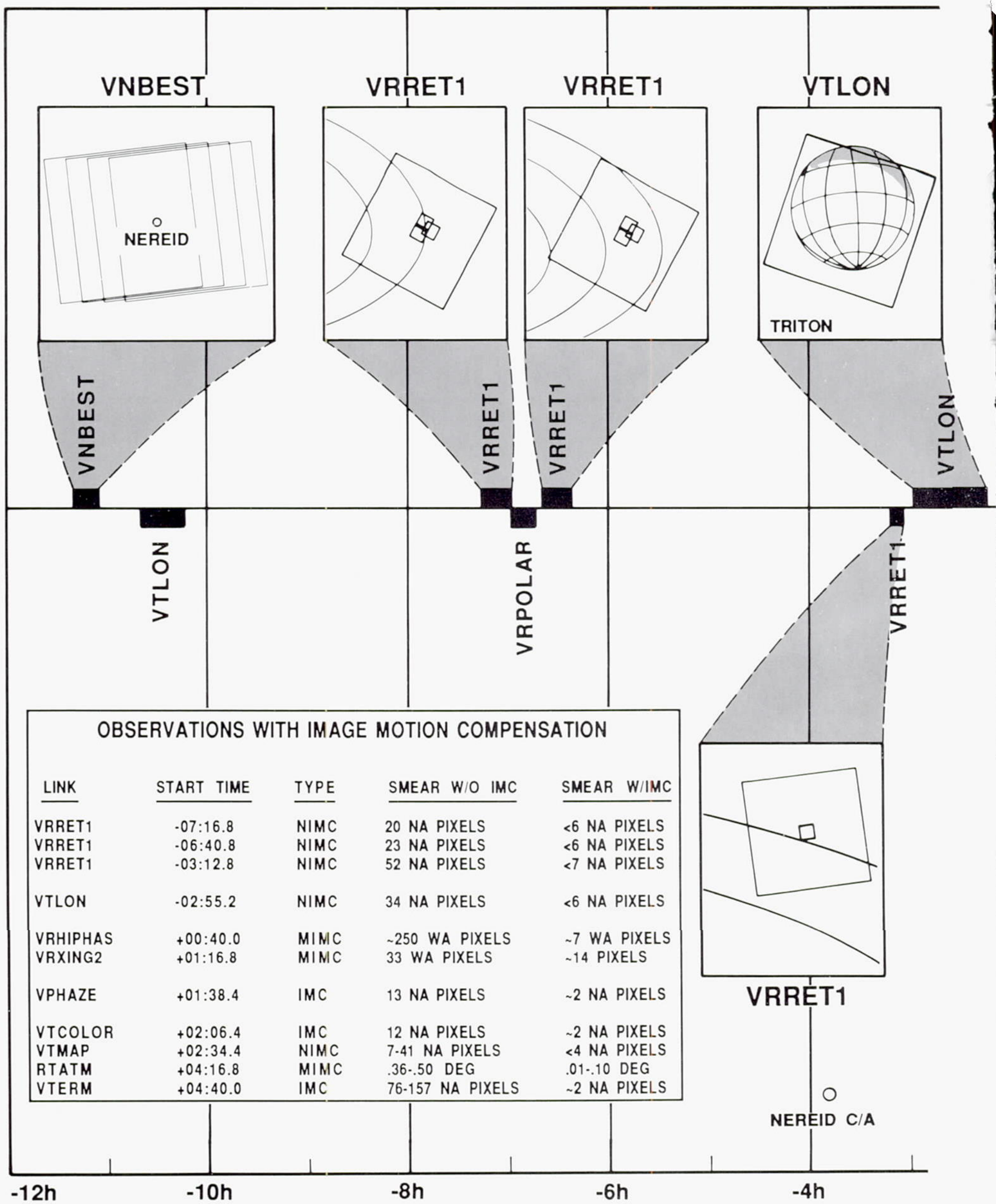
By now, it is clear where Voyager is heading: Neptune completely fills the wide-angle (WA) camera field of view, which looks at fifty times more viewing area than the NA camera. Even Triton, for so long just a few pixels across even in the NA camera, spans half-way across the NA view.

B951 starts with the X-band signal (during the XSGRAV link) controlled by a precise tone transmitted by the Canberra 70-m antenna. The DSN stations near Madrid then carefully listen to the return signal. With Neptune tugging on Voyager, there will be a measurable Doppler shift, which can then be used to deduce the strength of Neptune's gravity. After XSGRAV gets started, some great full-disk WA images of Neptune are taken using the VPWA link. While the first set of these images is being shuttered, the fields and particles detectors kick into high gear with high-rate samples of the flow directions of magnetospheric charged particles every six minutes. Then the cameras are slewed over to take the best picture we'll get of the small moon Nereid (via VNBEST), which will only fill about 20 pixels or so in the NA frame; Neptune was this size in January 1989. Next, a slew to Triton for a full-disk NA shot.

It's two hours into the load, and time for some classic Voyager science! Follow along with the visual view of what's happening in Figure 6-10 as we accompany Voyager 2 on its trek. This timeline shows the order of, primarily, the imaging links as Voyager executes them; the longer timeline in the Guide's "Hip Pocket" shows the order as received on Earth, including much of the late FE phase. Why the difference? Voyager can't send us everything in real time—some observations must be recorded first, and then played back to us anxious Earthlings later.

From N-10h to N-8h, the IRIS is trained on a spot in Neptune's atmosphere at -40.5 degrees south latitude, which is the latitude Voyager's radio signal will pass through as the spacecraft pops out from behind the planet at the end of its Neptune Earth-occultation experiment, 55 minutes after Neptune closest approach. Using the data collected from this observation (RPOCCPT), scientists can later determine the helium abundance at this occultation egress point, as it is called. These IRIS data provide pieces of the puzzle needed to determine the atmospheric structure and composition there.

After some ISS, IRIS, and PPS observations of Neptune's sunlit limb (edge), Voyager trains its cameras on the expansive ring-arc region for a while. Between N-7h 17m and N-6h 22m, two executions of the retargetable ring-arc link VRRET1 are completed, employing for the first time the clever Nodding Image Motion Compensation (NIMC) technique described in Chapter 9 to freeze the motion of selected clumps of orbiting ring-arc material. (The



OBSERVATIONS WITH IMAGE MOTION COMPENSATION

LINK	START TIME	TYPE	SMEAR W/O IMC	SMEAR W/IMC
VRRET1	-07:16.8	NIMC	20 NA PIXELS	<6 NA PIXELS
VRRET1	-06:40.8	NIMC	23 NA PIXELS	<6 NA PIXELS
VRRET1	-03:12.8	NIMC	52 NA PIXELS	<7 NA PIXELS
VTLON	-02:55.2	NIMC	34 NA PIXELS	<6 NA PIXELS
VRHIPHAS	+00:40.0	MIMC	~250 WA PIXELS	~7 WA PIXELS
VRXING2	+01:16.8	MIMC	33 WA PIXELS	~14 PIXELS
VPHAZE	+01:38.4	IMC	13 NA PIXELS	~2 NA PIXELS
VTCOLOR	+02:06.4	IMC	12 NA PIXELS	~2 NA PIXELS
VTMAP	+02:34.4	NIMC	7-41 NA PIXELS	<4 NA PIXELS
RTATM	+04:16.8	MIMC	.36-.50 DEG	.01-.10 DEG
VTERM	+04:40.0	IMC	76-157 NA PIXELS	~2 NA PIXELS

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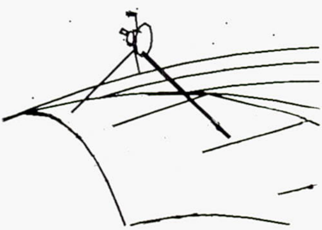
1989/08/25 4:00 GMT (SCT)

SPACECRAFT TIME OF VOYAGER-2



TO NEPTUNE: 29224 KM

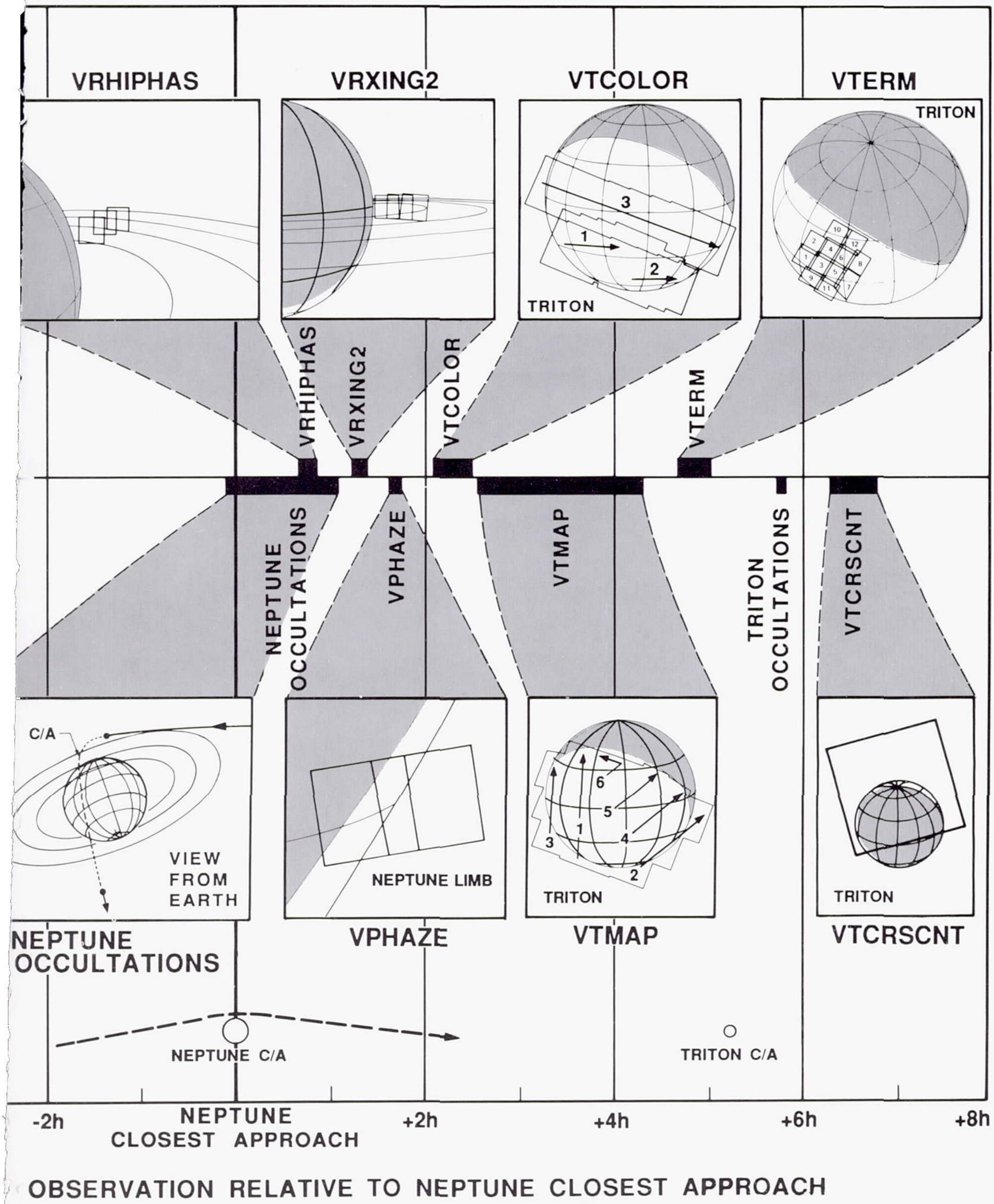


Figure 6-10. Data taken by Voyager 2 near Neptune closest approach.

table accompanying Figure 6-10 summarizes the dramatic benefits of the smear-reducing techniques used in B951.) A long exposure of the region above Neptune's north pole is made during this period as well in an effort to detect a hypothesized *polar* ring.

By N-5h 18m, a scan of Neptune's bright limb with the PPS and UVS is completed. Then for almost two more hours, it's back to the rings. Between N-4h 55m and N-3h 3m, Voyager conducts two similar observations. In PRSIGSGR and URSIGSGR, the sensitive detectors in the PPS and UVS instruments gaze at the star Sigma Sagittarii as it drifts behind the right-hand half of the ring-arc system as a result of Voyager's motion. This stellar occultation should reap a great harvest of detailed ring-arc region structural and orbital data. (This star helped us, in a sense, to point our finger at Voyager 2, remember?)

While the bright limb scans and stellar occultations above are executing, the bit stream containing the all-important B951 LSU parameters arrives and is loaded, having travelled from Madrid, Spain to the awaiting CCS in precisely 4 hours, 5 minutes and 57 seconds. Some extremely critical numbers reside in this LSU. For example, all Voyager science observations between about N-3.5h and N+9h are sequenced in what is called a movable block—three separate ones, actually. The first, the Neptune Movable Block (NMB), holds all activities around Neptune closest approach from N-3h 20m to N+1h 46m; another, the Triton Movable Block (TMB), contains the observations around Triton closest approach from N+1h 50m to N+8h 38m; the third, the Vernier Movable Block (VMB), encompasses the critical sequence for controlling the Neptune radio science occultation from N-5m to N+56m, and overlays the NMB.

One thing the B951 LSU does is tell Voyager's CCS units how much to shift these movable blocks in time. By allowing the entire block of activities in each block to shift, timing errors can be removed from the whole set in one simple step, instead of changing individual timing parameters in each observation. (There are so many observations during this busy period that using the piece-by-piece method would quickly use all available CCS words!)

Shifts in multiples of 48 seconds are possible for the NMB and TMB; for the VMB, a special technique is used that allows shifts in vernier multiples of only one second, independent of how much the NMB is shifted. The nature of the VMB is what forces the Navigation Team to estimate the time of closest approach to within one second. For everything except the critical radio science occultation, 48 seconds is good enough.

The other parameters in the B951 LSU control scan-platform pointing values to several high-value targets, maneuver rates for the radio science occultation maneuver, and rates for a critical Triton Image Motion Compensation (IMC) maneuver.

So, with its timing corrected by the NMB shift, Voyager 2 continues. By N-3h, another NIMC-controlled VRRET1 is done. Next, the last great image of Triton before Neptune closest approach is taken: VTLON, again using NIMC. Triton subsequently gets eclipsed by Neptune's southern limb, and won't be visible again until the spacecraft arcs over Neptune's pole. The scan platform shifts back to Neptune for some ISS, IRIS, and PPS photometry measurements. Neptune and Triton are so far apart now from Voyager's point of view that it requires a medium-rate scan platform slew to go between them, just to save valuable time. The Low-Energy Charged Particle (LECP) instrument switches into a higher-energy sampling mode as Voyager 2 penetrates the deepest part of Neptune's magnetic field and radiation belts. The other fields and particles instruments also make their contributions to the flood of data.

If you think things are busy now, think again . . . the next *eight* hours will really put Voyager 2 to the test!

At N-1h 41m, a medium-rate, elevation-only slew points the sensitive optics of the scan instruments away from Neptune—towards deep space—to protect them for the impending ring-plane crossing. Then, one hour from its aiming point, Voyager configures its radio transmitter for the ring-arc system and Neptune occultations, calibrates its antenna, and gathers baseline pre-occultation data until N-20m.

For about ten minutes centered around N-56m (plus or minus a few minutes—Voyager will be the first to know), the spacecraft crosses the ring plane just outside the suspected ring-arc region. The PWS instrument should pick up the sounds of microscopic (harmless) ring particles vaporizing as they hit the spacecraft. Voyager pops up and over this plane (as viewed from Earth) at 76,000 km/h (47,100 mi/h); it has gained 4200 km/h (2600 mi/h) in the last 30 minutes alone! Neptune is tugging harder . . .

Immediately after the expected ring-plane crossing, Voyager performs a 61-degree roll from Canopus to orient the fields and particles instruments for measurements of the charged particles that should be raining into Neptune's north pole along the magnetic field lines, perhaps causing auroral activity ("northern lights"). At the end of this roll, the spacecraft remains in All-Axes Inertial (AAI) mode, with its attitude controlled not by some outside source like the Sun or a star, but by the onboard gyroscopes.

By N-30m, Voyager 2 reaches 85,000 km/h (52,800 mi/h), and the gravitational acceleration effects become noticeable: it is virtually getting pulled in by Neptune, and its trajectory is bending. Tiny Voyager must feel like the planet has grasped it firmly, and is now flinging it as hard as it can during the spacecraft's close dive over the northern polar regions.

With pure X- and S-band tones emanating from Voyager, the radio science ring occultation (XROCC) begins at about N-8m, although the fringes of Neptune's ionosphere may affect these signals as early as N-20m. Back on Earth, the spacecraft rises above the horizon over the DSN sites in Australia. A bit more than four hours later, the signals from our remote beacon will land in the arrayed dishes, distorted in meaningful ways by their passage through the ionosphere, ring-arc system, and atmosphere.

It's N-5m. The duration of each of Voyager's thruster pulses is increased from four-thousandths of a second to ten-thousandths, just in case Neptune's atmosphere applies some unexpected drag on the vehicle, and also to provide quicker response to maneuver commands needed for the occultation experiment. This special provision will remain in place for the next hour. The shift of the VMB precisely controls the timing for all occultation activities during this interval—Voyager's finest hour at Neptune. Since the telemetry stream was turned off an hour earlier to concentrate power in the pure radio signal, all spacecraft telemetry is routed to the tape recorder for later playback.

Our explorer's speed relative to Neptune peaks at an impressive 98,350 km/h (60,980 mi/h) as it silently and effortlessly sails through its aiming point—right on target—a mere 4400 km (2730 mi) above Neptune's sensible atmosphere, and only 4850 km (3000 mi) above the methane cloudtops below. This is by far the closest Voyager 2 has been to any body since it left Earth twelve years ago. As it arcs over 77 degrees north latitude, it starts to slow down, and begins its permanent journey down and out of the ecliptic plane, thanking the gravity-assist effect for the ride.

As the craft sinks behind the dark side of the planet, Neptune's sunrise terminator passes beneath, and within about six minutes after closest approach, Voyager watches with a special UVS Sun-viewing port as the distant Sun disappears into the ever-thickening atmosphere. The Neptune occultation has begun.

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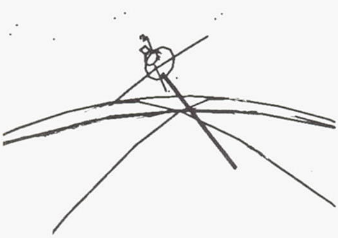


TO NEPTUNE: 32257 KM

With its pure-tone transmissions still turned on—and while completely out of view from the Earth—the automated spacecraft performs an amazing series of 24 maneuvers, controlled to a large degree by the numbers that were stored onboard with the arrival of the B951 LSU. This string of maneuvers, collectively known as the "limbtrack" maneuver, precisely points the boresight of the HGA to Neptune's limb, starting with the ingress point in Neptune's northern hemisphere, then around the left limb (as viewed from Earth), and ending with the egress point at -40.5 degrees south. The limbtrack maneuver takes about 48 minutes to complete, and took an enormous amount of work to design. As Chapter 5 explained, the radio signals are bent as they pass through Neptune's atmosphere. The limbtrack maneuver controls the pointing of the HGA to ensure that these signals are bent so they hit the Earth and, thus, the DSN arrays, Parkes and Usuda included. We will learn a great deal about Neptune's atmosphere, size, and shape from this experiment.

Incidentally, while Voyager 2 is orchestrating its limbtrack maneuver, it is also collecting fields and particles data, collecting IRIS and UVS data from Neptune's polar region, and also managing to take a series of three WA photos of the ring-arc system—this time from the other side, in forward-scattered sunlight. The last of these observations, VRHIPHAS, employs a new smear reduction ploy called Maneuverless IMC, or MIMC for short. Instead of moving the entire spacecraft smoothly to track the target, only the jerkier scan platform motion is used.

As the spacecraft emerges from behind Neptune at N+55m 8s—again watching with the UVS—it sees the Earth first, followed by the Sun 49 seconds later. It continues to point its HGA at Earth for the outbound XROCC, and takes a nearly edge-on shot of the ring-arc system (VRXING2) just before its descending ring-plane crossing at N+1.5h. (VRXING2 is a three-WA-image MIMC observation also.) Then, as a thin bright crescent begins to show in Neptune's southern hemisphere, Voyager takes a parting shot—for the next eight hours, anyway—of Neptune's limb. One of these crescent observations is the VPHAZE link, which employs Voyager's classical IMC for the first time during the Neptune encounter.

With this phase of its mission done, the spacecraft focuses its attention on Triton, although its high-paced routine of fields and particles data-taking continues unabated. Back at Earth, everyone is still in the final stage of preparations for receipt of the first ring-plane-crossing data and the occultation signals! And the late activities continue, with the B952 LEU, B952 uplink, and B971 LEU keeping everyone as busy as ever.

A roll is completed to the Alkaid lock star at about N+2h, primarily to orient the charged-particle instruments for magnetospheric measurements between Neptune and Triton while, at the same time, preserving good viewing of Triton for the long-awaited upcoming observations.

For the next three hours, Voyager soaks in its unique view of Triton with its IRIS, PPS, UVS, and ISS instruments. By now, the mysterious moon has grown to be twice the size of the NA view, and is still mostly sunlit. Figure 6-10 shows the three high-value observations from this period: VTCOLOR, VTMAP, and VTERM. All have been designed to bring out selected information from Triton's surface; all use some kind of smear-reduction technique, and thus promise to be among the sharpest set of pictures Voyager 2 has ever returned. (Recall that the NIMC and IMC parameters were sent up with the B951 LSU, and that the timing for this chunk of science is controlled by the TMB shift.)

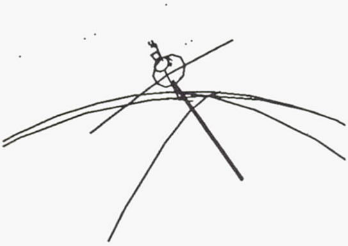
By this time, Triton's small gravitational tug can be felt by Voyager, allowing the scientists on Earth to measure the effects by changes in the radio signal. Speaking of those on Earth . . . many dozens are busy now monitoring the incoming Neptune occultation data; millions more are enjoying Voyager's show.

Triton closest approach occurs at N+5h 14m. Off in the distance, a star known as Beta Canis Majoris is about to get occulted by Triton. Voyager trains its PPS and UVS sensors on the star for about 20 minutes, watching its brightness change as it passes first through Triton's wispy atmosphere, then behind the moon, and back out again.

Then quickly, a medium-rate slew positions the UVS Sun port to the Sun, and the spacecraft configures its radio science equipment for another brief Earth and Sun occultation period. For nearly forty minutes, Voyager holds its attitude steady as it watches the two orbs of light, which wink out behind Triton from about N+5h 43m to N+5h 47m, recording all of its data as it goes.

About 17 minutes after the Triton occultations, the spacecraft rolls back to where it started seven hours earlier, on Canopus lock, to permit unobscured viewing back towards Triton and Neptune. VTCRSCNT will show a thin bright sliver of sunlight smiling from the limb of an otherwise dark face of the moon. Next comes a two-hour series of IRIS, PPS, and UVS observations of Triton's disk and atmosphere.

It's now N+9h, we're at the end of the TMB. More importantly, the CCS is nearly out of words for sequence control! It's amazing that Voyager just did so much in B951 with so little onboard memory (some 2200 18-bit words, or about 5 kilobytes), but thanks to the ingenuity of many Earthlings, it did.



For 17 more hours, in conjunction with continued frequent sampling of fields and particles data as

Voyager passes through Neptune's magnetotail, the scan platform gazes back at the Neptunian system, taking in more observations with its various sensors.

At N+13h, Voyager 2 sinks below the horizon in Australia. The Madrid DSN site steps in to continue our watch on Voyager.

By N+1d, collection of fields and particles data slows down considerably, and Voyager takes a breather, its tape recorder nearly full. It is already over 1.5 million km (930,000 mi) from Neptune and has slowed to 61,200 km/h (38,000 mi/h), only sixty percent of the speed it had just a day earlier, and only five percent faster than the speed of its eventual solar system departure.

Between N+21h and N+1d 16h, the IRIS and UVS scan from north to south across Neptune's disk in a repetitive sequence, having too few CCS words to do much more. At N+1d 16h 42m, the B951 load clocks out and B952 carries on with the encounter, for exactly three more days.

One of the big priorities in B952 is to unload the high-value data stored in Voyager's tape recorder and send it to Earth. This is achieved with a series of long playbacks scheduled over most of the load. In fact, as B971 (the first PE load) is being uplinked, the final playback is still in progress. The nominal plan is to have two playbacks of all high-value science completed by N+4d.

The long figure in the Guide's Hip Pocket shows two mosaics of the ring-arc system that come down from Voyager 2 in B952, VRMOS2 and VRNGARCS. In forward-scattered sunlight, these views may turn out to be quite revealing, as similar images were at the other encounters on the Grand Tour. A ring-arc movie much like those "filmed" during Neptune approach is also made during the last day of B952.

Various IRIS, PPS, and UVS maps and scans are completed during this load as well. About midway through, VTAURZAP checks for visual evidence of aurorae or lightning at Triton. And for about 11 hours starting at N+3d 6h, the high-value UPCORONA link searches for UV emissions around Neptune's disk, which helps in the determination of the composition of escaping gases.

A change in lock stars occurs two days into this load. A brief 15-minute dwell on the star Spica allows the LECP instrument to get a better sample of the charged-particle flows in the downstream solar wind and their interaction with particles in Neptune's nearby magnetic tail. About this time, Voyager 2 should be leaving Neptune's bubble-like magnetosphere and the surrounding bowshock, heading about 40 to 45 degrees south of the ecliptic plane.

By the end of the exciting NE phase, Voyager 2 will have already rewritten our understanding of Neptune and its neighborhood. Neptune's disk will again just about fill the NA camera view, but with a crescent this time, not a sunlit disk. Triton and Nereid—and probably a host of newly discovered objects—will appear as specks again.

But the show isn't quite over yet, because there's another high-value science observation to get, and lots of post-encounter cleanup work for Voyager to do.

Post-Encounter Phase (PE)

PE lasts a bit over one month. The B971 load is not quite two weeks long, while B972 is about three, as Figure 6-11 shows.

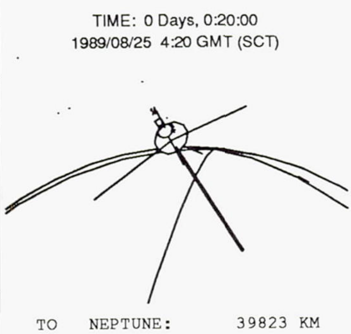
With the exception of a few Triton observations made by the UVS and ISS, all scan platform observations in this phase concentrate on Neptune and its ring-arc region. The highest-value observation in PE is the outbound RPDISK heat balance measurement, which starts just shy of a week after Neptune closest approach.

Proper pointing of the scan platform is essential for a successful RPDISK. If the actual amount of gravity-assisted trajectory bending Voyager gets from Neptune differs sufficiently from the best pre-encounter estimates, Neptune may not be centered in the IRIS field of view a week later, after the spacecraft has had a chance to speed millions of kilometers away, slightly off its anticipated course. To accommodate this uncertainty, the outbound RPDISK design employs a nine-position mosaic centered around the estimated position of Neptune's disk, rather than a steady gaze like we saw inbound.

But even this feature may not ensure success, even with the B971 LEU factored into the equation, since the data cutoff for this LEU had to be *before* Neptune closest approach! Enter the B971 LSU.

The data cutoff for the B971 LSU occurs at roughly the same time B971 starts—well after a good estimate of Voyager's outbound trajectory is available. Once the LSU reaches the CCS, the RPDISK observation is as good as done; the various teams that worked so long and hard for the previous three weeks on the late activities effort can move on to other encounter activities.

By midway through B971, about the same time the LSU reaches the spacecraft, Neptune and its ring system combined will fit within the NA field of view. As is evident in Figure 6-11, what's left of the encounter involves primarily calibrations, starting late in



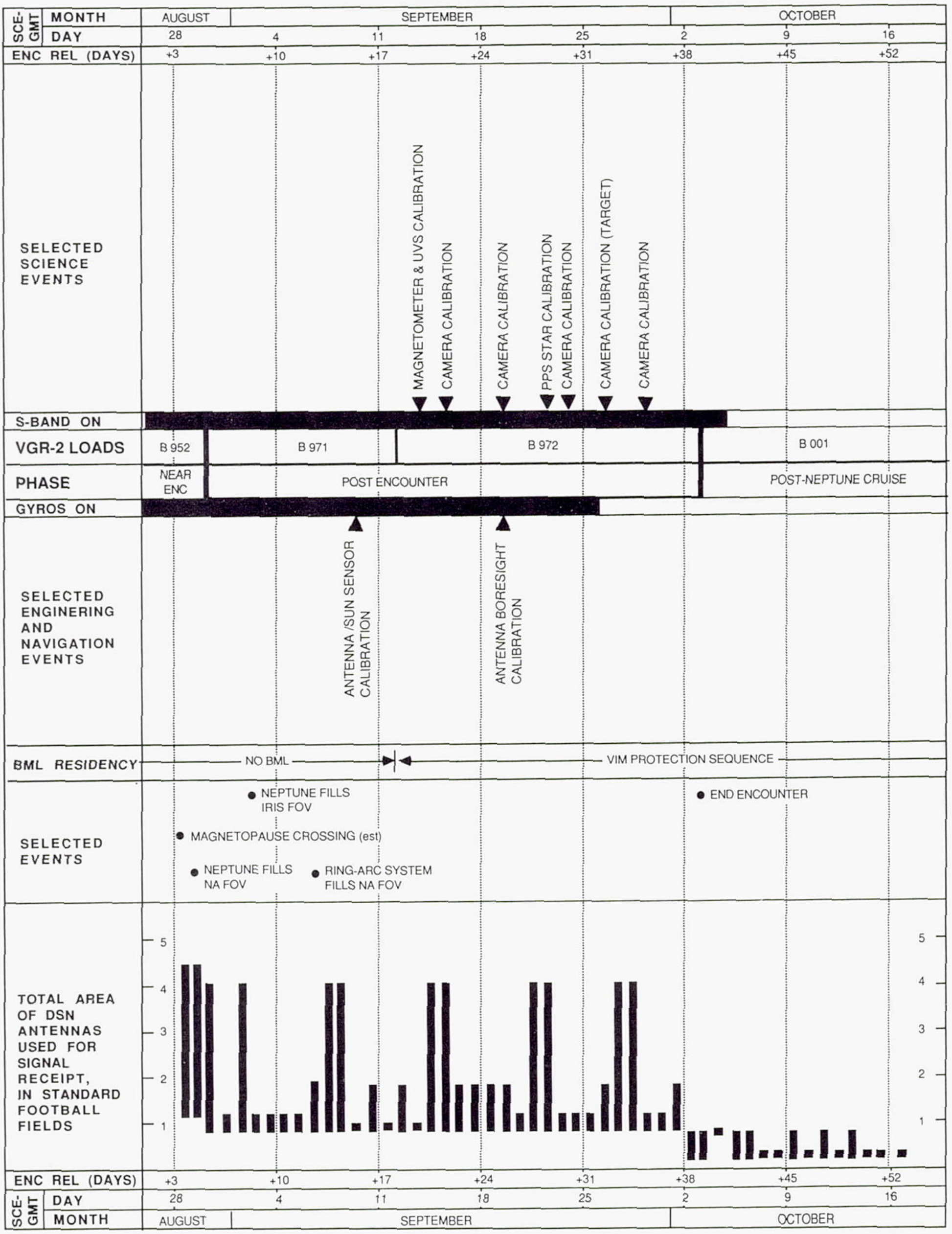


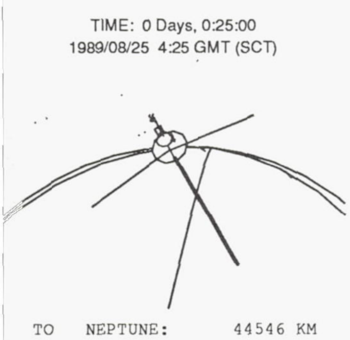
Figure 6-11. Voyager-2 Neptune encounter overview timeline for the Post-Encounter phase and early post-Neptune cruise.

B971, and continuing throughout B972. These calibrations supply post-encounter data points to compare with those taken in OB and FE. They are very critical to the future encounter data analysis efforts, so great pains will be taken to get them all.

With the uplink of B972, protection against failure of the remaining Voyager-2 receiver resumes via a small portion of CCS memory called the Voyager Interstellar Mission (VIM) Protection Sequence. This sequence provides limited BML-like protection, though much less than that designed into the pre-Neptune BMLs.

Now and then in B972, Voyager 2 will snap some parting shots of Neptune, perform a scan with the UVS or PPS, and take a sample of the fields and particles environment. About a month after its spectacular passes by Neptune, the ring-arcs, Triton, and whatever else it finds there, Voyager's gyros will be turned off. Approximately a week later, the DSN coverage drops to a bare-bones minimum, B972 clocks out, and the now-famous Neptune encounter—not to mention Voyager's Grand Tour—becomes a piece of exploration history.

Back on Earth, the Voyager scientists—data in hand—can continue the lengthy but enjoyable task of deciphering the secrets waiting to be found, and the solar system will seem evermore a bit smaller.



Any sufficiently advanced technology is indistinguishable from magic.

Arthur C. Clarke

7. *SLINGSHOT MAGIC*

You decided long ago that you wanted to go on a Grand Tour of exploration, and your destinations were clearly defined. Your ship is equipped with the latest in scientific instruments, onboard computers, and communications gear. The main problem is that your speed leaving Earth is not fast enough (considering the Sun's gravity) to carry you much beyond Jupiter—the first of your four destinations. To accomplish the trip, you must find a way to increase your speed relative to the Sun.

A nice fusion drive would do the trick—or maybe a matter/anti-matter engine—but these new technologies just aren't around yet. Fortunately, by selecting the proper flight path by each of your destinations, you will be able to "steal" some precious speed, fly on to the next more remote destination, steal some more speed, and complete your Grand Tour. Knowledge has saved the day, and your clever scheme will be called "gravity assist."

A Change in Attitude

The techniques used in the design of planetary missions really did not change all that much from the 1920s to about 1960. In the 1920s, Walter Hohmann discovered the lowest energy (least departure speed) path between any two planets. As shown in Figure 7-1, that path is an ellipse that is tangent to the orbits of both the departure planet and the destination planet.

Planetary mission design primarily consisted of determining the launch times for Hohmann transfer ellipses from Earth to the various planets. With the rockets that existed by the 1950s, it was thought that it would be a very long time before people could send spacecraft beyond the planet Jupiter. The energies required for even the "minimum energy" Hohmann ellipses to the outer planets were far in excess of what chemical rockets could deliver at that time.

Further complicating matters were the long travel times the Hohmann ellipses required. For example, an Earth-to-Pluto Hohmann ellipse required a 40- to 50-year one-way travel time. An Earth-to-Neptune Hohmann ellipse required a 30-year travel time. It seemed as though not many planets would be visited in our lifetimes.

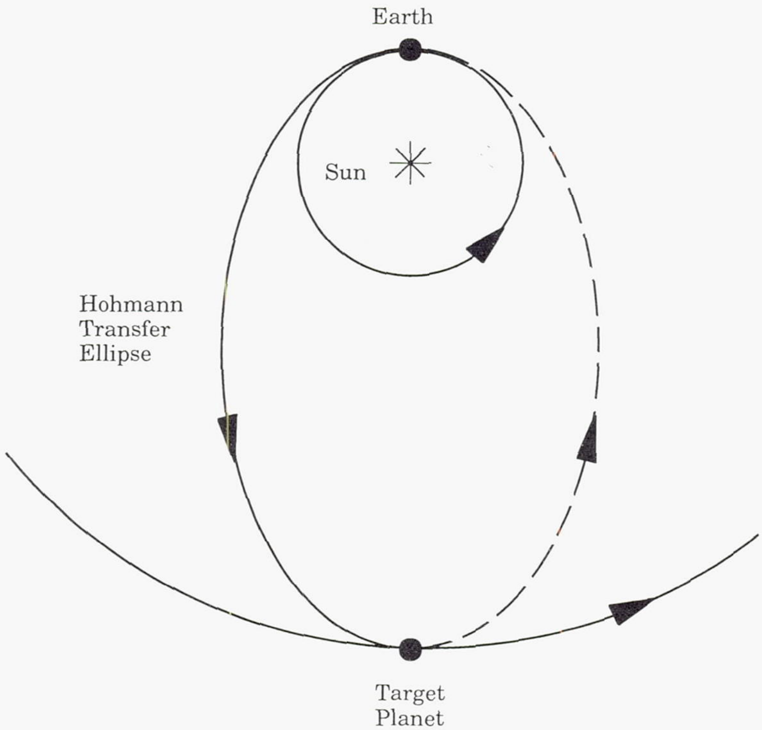
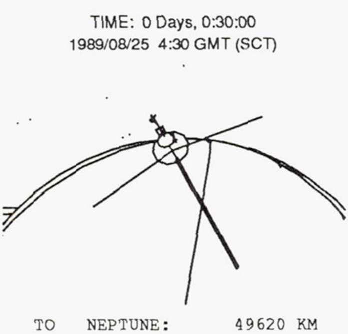


Figure 7-1. A Hohmann transfer ellipse, tangent to the orbits of both the planet one is leaving and the planet one is going to, requires the least departure energy or speed.

In the summer of 1961, a 25-year-old graduate student in mathematics, hired as a summer employee at JPL, created a revolution in planetary mission design. Michael A. Minovitch showed how to gain extra speed by properly selecting the path from planet to planet.

Minovitch wondered if the gravity field of a planet could be used to provide thrust to a spacecraft. Many others before him had thought about the effect of planetary gravity fields on passing bodies. But, by 1960, most planetary mission designers considered the gravity field of a target planet to be somewhat of a nuisance, something to be cancelled out, usually by onboard rocket thrust.



Minovitch was the first to show how to design a trajectory to a target planet in such a way that a gravity assist could be obtained from that planet to go on to another planet. Such a boost could be obtained from the second planet to go on to a third planet, etc. The only energy required would be the launch from Earth to the first planet. All subsequent planets were "free." As an added bonus, due to the gains in speed, the one-way trip times to each of the planets beyond the first were significantly reduced.

By 1962, Minovitch had realized that using the gravity field of Jupiter was the key to outer planet exploration. Jupiter is the largest planet and, as such, possesses the strongest gravity field. Jupiter could be used to quickly slingshot spacecraft to Saturn, Uranus, Neptune, and Pluto, making such missions possible for the first time. That same summer, Minovitch realized that launch opportunities to the outer planets, via Jupiter, were possible from 1962 to 1966 and then recommenced in 1976 until at least 1980. He graphically illustrated the trajectory of an Earth-Jupiter-Saturn-Neptune Grand Tour, using a 1976 launch.

In 1964, Maxwell Hunter publicized Minovitch's gravity-assist concept in an outer planets mission design paper. The next year, Gary Flandro (then at JPL, presently founder and president of Wasatch Research, Inc.) designed a set of Grand Tour trajectories using the gravity-assist concept, including an example of an Earth-Jupiter-Saturn-Uranus-Neptune mission. He pointed out that these planets align themselves for this mission only once every approximately 176 years. The next set of Earth-launch opportunities would occur in 1976, 1977, and 1978. This provided the impetus for what ultimately became the Voyager Project, including Voyager 2's Grand Tour of the outer planets.

Real Applications

The first application of the gravity-assist concept for planetary exploration occurred in Mariner 10's Venus/Mercury mission. The Mariner 10 spacecraft was launched from Earth in 1973 and travelled directly to Venus via a Hohmann transfer ellipse, using the gravity-assist technique at Venus in February 1974 to get a boost on to Mercury. At Mercury in March/April 1974, Mariner 10 received a second gravity assist, which allowed the spacecraft to encounter Mercury a second time, in September 1974. A third gravity assist was performed at the second Mercury encounter to enable a third and final Mercury encounter in March 1975.

The second application of the gravity-assist concept occurred as a part of the Pioneer 11 mission. This spacecraft was originally intended to encounter only Jupiter (in 1974), as a precursor to the Voyager-1 and -2 encounters. However, the opportunity existed to execute a gravity assist at Jupiter to go on to Saturn, and Pioneer 11 was able to take advantage of this opportunity. Pioneer's gravity-assisted turn was almost 180 degrees, causing the spacecraft to travel all the way back across the inner solar system to pass closely by Saturn five years later, in 1979.

Meanwhile, at JPL from 1974 to 1976, Paul Penzo, Andrey Sergeyevsky, Joseph Beerer, and Charles Kohlhase evaluated the merits of over ten thousand different Voyager trajectories. The objective of the study was to maximize the total amount of knowledge that could be gathered from the Jovian and Saturnian systems. Of primary interest were Jupiter's moon Io and Saturn's moon Titan. Each pair of Voyager 1 and 2 trajectories had to have at least one close approach to each of these two moons. Additionally, the best trajectories had the largest number of close flybys of the remaining Jovian and Saturnian satellites. The final trajectories flown are shown in Figure 1-4, and include two gravity swingbys at Jupiter, two at Saturn, one at Uranus, and one at Neptune.

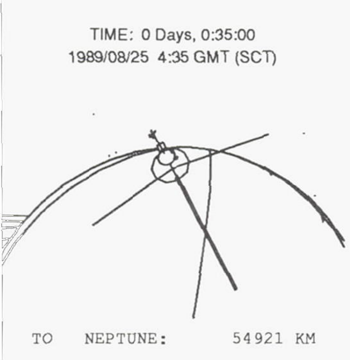
Gaining Speed Along the Way

Gravity assist is created by causing a spacecraft to pass by a planet in a carefully controlled manner, as shown in Figure 7-2. A spacecraft may pass by the trailing (or leading) hemisphere of a planet. The close passage causes two things to occur. First, the spacecraft's path is bent. Second, the spacecraft either gains or loses energy (speed), as described below.

The bending occurs regardless of whether the spacecraft passes by the leading or the trailing hemisphere. The direction of the bending is selected by picking the proper hemisphere. The amount of bending is controlled by picking the closest approach distance to the planet. The bending in the flight path occurs both with respect to the planet and with respect to the Sun.

There is no *net change* in speed, however, *with respect to the planet*. The spacecraft is in continual free-fall with respect to the planet. Its final speed (far after approach) is exactly the same as its initial speed (far before approach) *with respect to the planet*.

With respect to the Sun, the story is quite different. First note that the spacecraft's velocity relative to the Sun is always equal to the spacecraft's velocity relative to the assisting planet *plus* (vector addition) that planet's velocity relative to the Sun. *From the point of view of the Sun*, when comparing the pre- and post-swingby spacecraft velocities, Figure 7-2 shows that this results in a net increase in the speed of an outbound (i.e., going away from the Sun) spacecraft (and, not shown in the figure, in a net slowing down of the planet). Energy has been transferred from the planet to the spacecraft. On the other hand, if an outbound spacecraft passes by the leading edge of the planet, from the point of view of the Sun, the roles are reversed: the spacecraft slows down and the planet speeds up. In



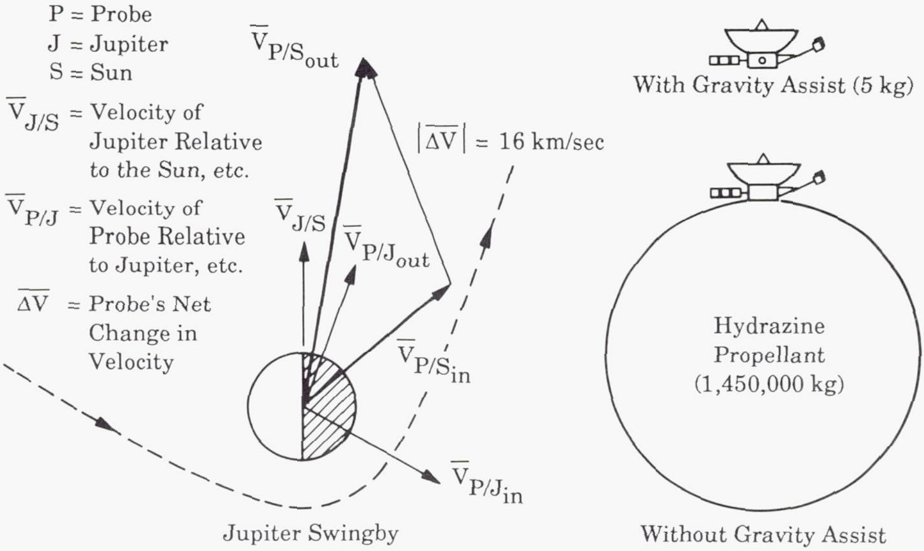


Figure 7-2. Passing close by a massive body causes a spacecraft's path to be bent, and energy to be exchanged between the spacecraft and body. In the Voyager-1 Jupiter swingby shown, there is no net speed gain relative to Jupiter; however, Voyager 1 gained 16 km/sec (35,700 mph) relative to the Sun, and Jupiter lost 1 foot per trillion years relative to the Sun, causing its orbital period to shrink by nearly one nanosecond.

the case of Voyager 2, this may be seen in Figure 11-6, which dramatically shows the behavior of the craft's Sun-relative speed as it swings past each of the Jovian giants enroute to escaping from the solar system. These principles also apply to gravity-assist applications using the large satellites of a planetary system.

Voyager 1 at Jupiter and Voyager 2 at Jupiter, Saturn, and Uranus passed by the trailing hemisphere of the respective planet, gaining speed at the expense of each planet. However, Voyager 1 passed (slightly) the leading hemisphere of Saturn, and Voyager 2 will pass (slightly) the leading hemisphere of Neptune. In these two cases, the spacecraft slowed down and the planets speeded up.

Diving for Triton

Neptune is Voyager 2's last planet. There being no next planet to seek (Pluto is not reachable; refer to Figure 6-2), Voyager 2 is not limited to passing Neptune through any particular gravity-assist corridor, and can instead concentrate on Neptune's large moon, Triton. Triton is as interesting to many planetary scientists as Neptune is. Triton is large enough to have an atmosphere. Its surface temperature and pressure are close to the triple point of nitrogen, raising the possibility of nitrogen clouds, frozen nitrogen *pools*, and snow/ice on the surface.

In 1980, Andrey Sergeyevsky discovered that there was indeed a way to pass closely by both Neptune and Triton, thereby maximizing the scientific return from each. The means was a final application of the gravity-deflection concept. The spacecraft would pass very close to Neptune (within 4850 kilometers of the cloud tops) in order to bend its path by about 45 degrees to pass close by Triton 5.2 hours later (see Figure 6-1.) The close passage of Neptune occurs near its North Pole, and is just barely on the leading hemisphere. Voyager 2 will slow down slightly (and Neptune will speed up even more slightly) as a result of this final gravity assist.

The Solar System is Ours

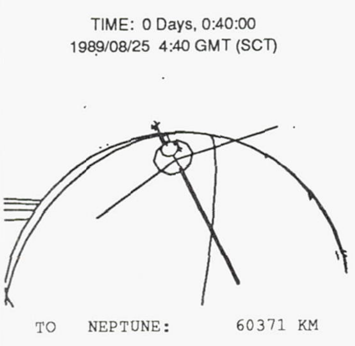
Before Minovitch applied his gravity-assist design concept, planetary spacecraft were limited to visiting Mercury, Venus, Mars, and Jupiter. Using gravity assist, missions to all the planets are possible. Spacecraft have travelled directly to Venus, Mars, and Jupiter. Mercury, Saturn, Uranus, and (as of the summer of 1989) Neptune have been visited via gravity assists. A mission to Pluto, using a Jovian gravity assist, will undoubtedly occur someday.

The next planned applications of the gravity-assist technique involve the use of planetary moons to provide the assist to planetary orbiters. Planetary systems that have large moons can be toured by using the gravity of the large moon(s) to deflect the spacecraft's orbit each time around.

The Galileo orbiter of Jupiter will perform ten gravity assists at Io, Europa, Ganymede, and Callisto, creating ten very close encounters of the latter three moons, and an additional three relatively close encounters. Galileo is due to launch in the fall of 1989, and will perform gravity assists at Venus (in 1990), and at Earth (1990 and 1992), before arriving at Jupiter in 1995.

On the drawing boards is a Saturn orbiter gravity-assisted touring mission. Forty gravity assists at Saturn's large moon Titan are planned for the Cassini spacecraft, leading to four very close passages and twenty-six relatively close passages of other Saturnian moons. Cassini is due to launch in 1996, and will perform gravity assists at the Earth (in 1998), and at Jupiter (in 2000), before arriving at Saturn in late 2002.

For more information on Galileo and Cassini, see Chapter 16.



If there are two or more ways to do something, and one of those ways can result in catastrophe, someone will do it.
Captain Murphy to Major Stapp, 1949[1]

8. SPARRING WITH THE GOBLINS

In Chapter 3, you were introduced to the variety of efforts conducted here on Earth that are essential to the success of a mission as complex as this one, far away at Neptune. And in Chapter 4, you learned about the remarkable robot called Voyager 2 that was designed to carry it out, in conjunction with the facilities of Earth Base.

People created, designed, and built all of this technology, and it is people who plan, execute, and monitor the mission. Perhaps this is why things don't always proceed as expected. There are goblins lurking everywhere—on Earth, on Voyager 2, and even at Neptune—and they are constantly scheming to trip us up, to interrupt the wealth of data streaming back from our remote, electromechanical emissary.

In this chapter, we will examine what is called contingency planning. A contingency is an event or situation that, if it occurs, can cause a reduction in the quantity and/or quality of returned Voyager data. Since the fundamental purpose of Voyager 2 and all that supports it is to return these data to Earth, then the purpose of contingency planning is to preclude goblins in the first place, and to preserve the data return when some goblins do sneak through our defenses.

None of the contingencies we get concerned about has a particularly high chance of happening; most are estimated to be less likely than one chance in twenty on an annual basis. Nevertheless, a chance is a chance, and it is prudent to take some actions in many cases.

In spite of everyone's contingency planning efforts, unexpected goblins can strike suddenly. Things simply go wrong and we are faced with a potential loss of valuable data. Once the Voyager system is attacked, a diligent effort ensues to determine the goblin's precise hiding place and to arrest and survey the inflicted damage. A thorough study of the precise cause of the problem is then conducted, leading to a recommended solution (or "fix") for that problem. If possible, methods and procedures are devised which essentially inoculate the Voyager system against future reappearances of the goblin that precipitated the problem.

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[1]This is the original wording for Murphy's Law. See the end of this chapter for the story . . .

Figure 8-1. ***Goblins, like the spacecraft-munching Great Galactic Ghoul (once sketched in fun, when early spacecraft seemed to experience problems when they reached certain distances from the Sun), are lurking everywhere. With well-laid contingency plans, however, we hope to thwart their evil intentions.*** *(Artist: G.W. Burton.)*

Let's review some Voyager history first, then look at these goblins more closely, and see what is done to outwit them.

Past Skirmishes: The Aches and Pains of Voyager 2

The Voyager contingency planning effort started well before launch, during the mission and spacecraft design phase, and continues to this day. Staying one step ahead of the goblins is a vigil that can never cease until each Voyager meets its ultimate demise.

To no one's surprise, goblins have been encountered all during this project (starting as early as the launch-through-Earth-departure flight sequence), as they are during all complex projects. Some have been stopped in their tracks by the various contingency planning provisions, but many have sneaked by. Nevertheless, it is a tribute to the keepers of Voyager 1 and Voyager 2 that both spacecraft are operating well after nearly 12 years in space. In fact, in many ways, both are operating with more capability than they had at launch, as the next chapter will show.

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Past skirmishes with the goblins have inflicted their wounds on both spacecraft; fortunately (since it is going to Neptune), Voyager 2 is probably the healthier of the two, considering that both of its FDS memories are still usable. Table 8-1 summarizes the lasting aches and pains that it has suffered along the way on its Grand Tour of the outer solar system, and includes the "treatment" prescribed and administered to circumvent the injury. In spite of the failed units, degraded components, and sporadic anomalies, we are coping with the problems. Most importantly, all ten of Voyager 2's science instruments are functional, as is the radio equipment. Thus, barring a severely damaging onslaught by the goblins, we are confident that investigations in all eleven science experiment categories will be successfully carried out at Neptune.

Table 8-1. Voyager 2 has felt its share of aches and pains over the years since launch, but Earth's doctors (the Flight Team) have taken admirable care of their distant patient.

Voyager 2 Health and Status	Actions Taken by Project/Comments
• Overall condition	
• No serious problems	• Except for consumables, spacecraft is operating with more capability than at launch
• All science instruments functional	• Expecting investigations in all science experiment categories at Neptune
• Failed components	
• Receiver 1	• Using special "best-lock frequency" tests and procedures. Carefully managing Voyager power and thermal states; "backup mission loads" stored on board to provide science return should Receiver 2 fail
• Receiver 2 signal lock circuit	
• Degraded components	
• One memory word lost in FDS A; 256-word block lost in FDS B	• No longer using these memory locations
• Azimuth actuator seized at Saturn; okay since	• High-rate slewing banned; other slewing limited; using special actuator health tests; on-the-shelf R951 CCS load design
• Some PPS filter and analyzer wheel selections lost	• No longer using these selections
• Decrease in narrow-angle camera vidicon cathode emission	• Imposed constraints on total on time, on-off cycles, and diagnostic data readout
• Weakening IRIS interferometer and neon cathode emission	• Imposed special thermal conditioning constraints
• PWS and LECP sensitivity decrease	• Implemented special sequencing and and procedural fixes
• Spurious resets in PRA electronics	• Special autonomous reset sensing/correction routine active on board

The Goblins and Their Mischief

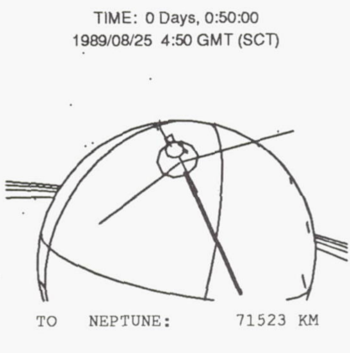
Goblins generally come in three varieties. There are those in the "human element" category, spawned by our innate tendency to err. Whether they are called "operator error," "cockpit error," or "indeterminate cause," they all can be traced to the same source: we humans simply make mistakes once in a while. Another type is the more common "glitch", when seemingly perfect hardware or software suddenly hiccups and goes into an unanticipated operating mode, or even worse, stops working altogether. Sometimes the glitch is more gradual and drawn out, in which case it may be called a "graceful degradation." A third species of goblin is "acts of nature"—those natural environmental effects and hazards that are commonly associated with space travel: radiation, temperature extremes, dust and debris, physical uncertainty, and the like. Natural factors on Earth such as stormy weather and earthquakes influence the contingency plan as well.

The goblins tend to concentrate their mischief in three areas: the Computer Command Subsystem (CCS) sequence development process, the telecommunications link between Earth and Voyager, and on Voyager itself.

As you found in Chapter 3, the CCS load generation process is lengthy, requiring the concerted efforts of dozens of people using sophisticated computer programs and simulators to take the explicit sequence requests and convert them into a complex string of 1s and 0s that will tell Voyager 2 to do exactly what we want it to do, and nothing else. Such a system is open ground for the goblins, prone to human error. A tightly woven network of sequencing rules, reviews, checks and balances, and constraint checking is required throughout the sequence development process to ensure that a near-perfect sequence is generated. This activity—which could be described as building software that must work the first time—makes extensive use of people, computers, and seemingly endless coordination meetings.

Voyager 2 is so far away from us now that managing telecommunications—commanding the spacecraft and receiving and routing its telemetry—is an imposing and challenging task. The DSN antennas must be precisely pointed, as must the spacecraft. All data rates and modes must be matched. State-of-the-art DSN receiving gear must be maintained. Margins must be added into the performance envelopes to account for possible degradations in signal level due to pointing offsets and weather. Timing is often critical. Again, this is open territory for goblins of many types.

And, in spite of its stupendous string of successes to date, Voyager 2 is still a vulnerable piece of



technology, susceptible to the hazards of space and, perhaps more importantly, aging. Some resources on board are consumable, such as the hydrazine fuel for the thrusters. Other components most certainly have limited operating lifetimes, such as the radio transmitter tubes, or subassemblies with moving parts such as the digital tape recorder and scan platform actuators. Electronic devices and switches, though generally quite reliable, can fail permanently—and quite unexpectedly. These spacecraft-borne problems can often take a considerable effort to understand, since all we have to look at is the overall spacecraft performance and limited telemetry data. A repair visit to Voyager 2 is simply beyond our reach.

Anomalies more often than not arise from changing the normal way of doing things. As you will find in the next chapter, new challenges at Neptune have demanded some changes in the way we operate Voyager 2 and its support network. These changes, in turn, are a potentially rich source of goblins, and have required a fresh look at the contingency plan for the mission. Much of this plan is based on contingency preparations completed prior to the 1986 Uranus encounter, adjusted somewhat for Neptune to reflect the upgrades in telecommunications capability, enhancements to spacecraft performance, different encounter characteristics, and the ramifications of being 50 percent farther from the Sun.

Before we see how the contingency plan addresses all of this, let's first look closely at perhaps the most significant driver of this plan: environmental hazards in the Neptune system.

Taking the Plunge

Voyager 2's north polar trajectory places the spacecraft closer to Neptune than any other outer planet encounter to date, and thus potentially closer to various environmental influences there (see Figure 8-2). Assessment of the risks posed by this near encounter with Neptune required models of its ring system, magnetosphere, atmosphere, and obscuration periods—times when the spacecraft cannot precisely sense the Sun or stellar (star) reference because either Neptune, its ring-arc system, or Triton is in the way. As Voyager 2 plunges through the Neptunian system, slam-dunking its way toward Triton, all four environmental goblins have the potential of catastrophically disrupting the encounter, so something must be done to protect our fragile craft.

As you learned in Chapter 2, the ring system at Neptune is apparently quite different than those observed at other gas giants, mainly because of the evidence for patchy ring arcs rather than continuous rings. In addition to the ring-arc region, past experience at other outer planets and current theory

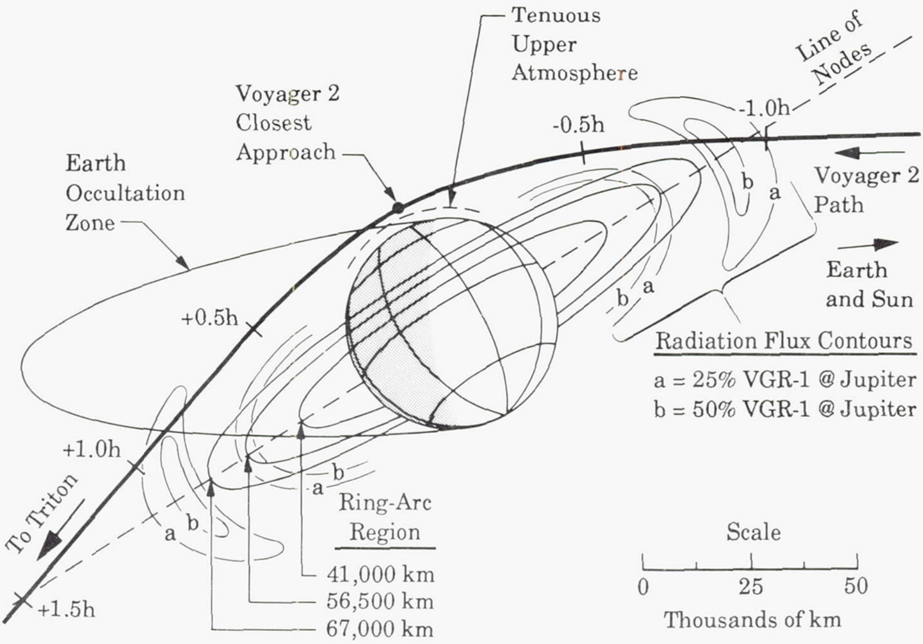


Figure 8-2. We are looking perpendicular to Voyager-2's path through the environmental hazard zones. Table 8-2 summarizes the periods during which we think the goblins have the greatest chance to do their mischief.

suggest that a diffuse, thin disk of ring material is likely inside, and possibly outside, the inferred ring-arc system. Such diffuse rings were observed by Voyager in and around the main rings at Jupiter, Saturn, and Uranus, and were penetrated (out beyond the main rings) without damage to the spacecraft at the latter two planets.

The Project's overriding concern about rings focuses on the possibility that Voyager 2 might impact ring particles and suffer a significant degradation of a subsystem or instrument capability, or worse yet, a catastrophic failure. This concern is heightened by the fact that Voyager 2 first crosses the ring plane before most of the high-value encounter science is collected.

Extensive analyses of the ring issue have led to a consensus on one important point: the probability of actually hitting a narrow ring arc with Voyager 2—even if we wanted to—is very low (less than 1 percent). The concern really is, then, the unseen diffuse disk of material, especially during the inbound ring-plane crossing, which is closer to the planet. Unfortunately, no direct observations of this purported sheet will be obtainable using ground-based telescopes, and the chance of getting a defini-

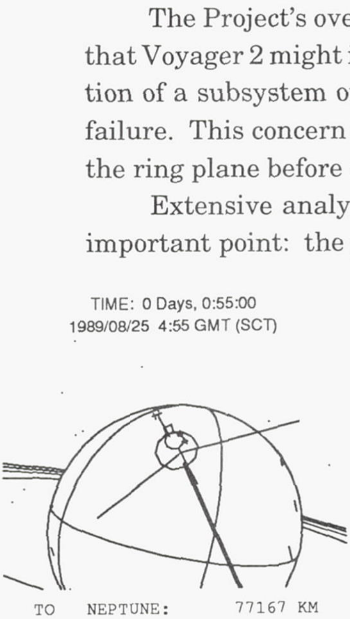


Table 8-2. Periods of Greatest Vulnerability

• Diffuse Disk of Ring Particles	
Inbound Ring-plane Crossing	-1h 8m to -44m
Outbound Ring-plane Crossing	+1h 11m to +1h 49m
• Radiation	
Peak Radiation Inbound	-60m to -20m
Peak Radiation Outbound	+40m to +50m
25%, 50%, 75%, 99% Dosage	-50h, -30m, +40m, +60m
• Atmosphere	
Drag, Heating and Arcing	-5m to +5m
• Obscuration Zones	
Neptune	-1h to +2h
Triton	+5h 20m to +6h 10m

tive observation with Voyager-2 pictures is considered extremely low until after Neptune closest approach, when the sheet might be visible in forward-scattered sunlight, much like when dust or dew is visible on your car windshield when driving into the Sun.

By choosing a trajectory just outside where we think the ring-arc region ends (assuming equatorial rings, as shown in Figure 2-9), we can avoid the most likely locale for concentrations of this diffuse material. Such a path thus directs the threat of goblins to the possible region of diffuse material outside the ring-arc region—a threat found to be idle at Saturn and Uranus because the dust particles in this region were so small and dispersed. If Neptune has polar rings, however, as a few scientists have suggested, Voyager 2 could cross an *inner* diffuse sheet—a threat of some concern.

Another Neptune system environmental hazard is radiation. Severe radiation can damage Voyager's science instruments and subsystem hardware, degrade performance, create calibration difficulties, cause onboard timing errors, cause frequency shifts, and inject unwanted noise into various data paths. The Flight Data Subsystem (FDS) is considered vulnerable to this radiation as well. Predicting the magnitude of these effects is an imprecise science even when the radiation environment is known exactly, much less when next to nothing is known about it, as is the case for Neptune. The planetary magnetospheres that trap this radiation are so large that these effects are generally independent of small trajectory changes, so at Neptune, this is one goblin we must live with.

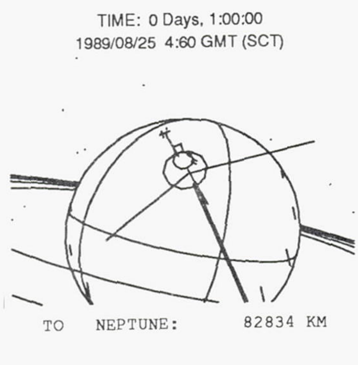
To evaluate this hazard to Voyager 2, a model of energetic electrons was required. Voyager 1 experienced several temporary and permanent hardware degradations and failures when subjected to radiation as it passed near Jupiter, and this radiation was subsequently correlated with such high-energy electrons. Voyager 2 is passing even closer (relatively) to Neptune, so a potentially greater radiation hazard would be likely if Neptune's magnetosphere matched Jupiter's. However, according to present understanding, Neptune's magnetosphere is more likely to resemble that of Uranus in size and intensity. On the path Voyager 2 will take, the present Neptune radiation model predicts a peak radiation "flux" level 57 percent as strong as the Voyager-1 Jupiter level, and a total radiation dosage of only 3 percent of the Voyager-1 Jupiter level; both levels are considered safe.

The next environmental goblin—the atmosphere—can produce effects that have barely been considered during past Voyager encounters. Voyager 2 is aimed for a region on the fringe of Neptune's atmosphere, where effects such as loss of attitude control (due to drag), heating, and corona discharge between high-voltage components are possible, centered around Neptune closest approach. With the proper aim and some clever operational tricks, however, Voyager 2 will pass beyond the grasp of this goblin, as we shall soon see.

Calculation of obscuration periods is primarily a geometric problem once the desired trajectory is selected and the various positional relationships of the Neptunian system are generally understood. The uncertain nature of the postulated ring-arc system adds a special twist to these calculations, since the individual arcs may partially block the Sun or stars and confuse Voyager's sensors.

Outwitting the Goblins

With so much operational experience behind us (including an ample set of anomalies), it is not terribly difficult to anticipate most plausible anomalies that might occur, and even some that aren't so plausible. The challenge facing Voyager personnel, therefore, is not in generating a long list of potential goblins, but in formulating an effective defense against them without overextending available resources. There are lots of goblins, but we simply do not have unlimited supplies of people, time, computer resources, and money with which to mount our defense, so these resources must be balanced between the efforts required to develop the nominal mission plan and those required for the contingency plan. The end result is that only some of the possible contingency provisions get implemented, and calculated yet conservative risks are taken.



As mentioned before, the contingency planning efforts for the Neptune encounter started first with an update of the plan devised for Uranus. Goblins that could lead to a science loss were then postulated and ranked to determine contingency work priorities. The ranking exercise considered criteria such as probability of contingency occurrence, the abruptness of the occurrence, the data loss potential, the recovery time required if unprepared for the anomaly, and the effectiveness of the proposed contingency protection. This entire effort took most of a year to complete (mid-1987 through mid-1988).

The primary goal of the contingency protection is to ensure an adequate defense against goblins in the critical near encounter CCS load, B951. This two-day load includes closest approaches of Neptune and Triton and associated Sun and Earth occultations, most of the top-priority science observations for the entire four-month encounter, and all of the environmental hazard periods. Once this protection is provided, remaining project resources are allocated to define other protective measures for events with unique timing or placement requirements, such as maneuvers and geometry-unique science observations. Generic protection techniques applicable to all CCS loads (including cruise loads) have also been devised.

So, keeping in mind the nominal sequence of events outlined in Chapter 6, here are some of the more interesting examples of contingency provisions that have been implemented (in addition to those in Table 8-1) to keep the goblins subdued and in check.

LOSS OF ONE CCS. All CCS loads can be modified in about three days to make them execute out of only one CCS. The penalty is that a moderate to significant amount of science must be excised from the original load to allow it to fit in the limited memory of one CCS unit.

LOSS OF ONE FDS. A very clever set of FDS programming features and CCS load design rules allows each CCS load to execute virtually without modification if an entire FDS is lost. Earth-based operators would be busy for a few days loading in the Neptune Single Processor Program (NSPP) and getting everything set up for this mode of operation, but most of the expected science and engineering data would still be returned. This capability is new for Neptune.

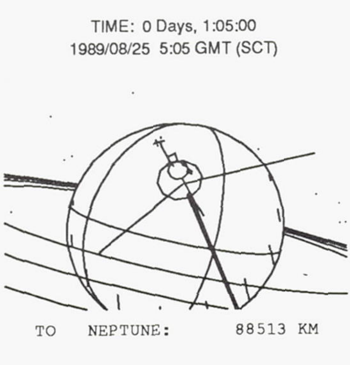
AVOIDING THE ENVIRONMENTAL HAZARDS. It was mentioned above that a path has been selected for the Neptune encounter that avoids most of the ring hazard by sending the inbound spacecraft through, at most, a diffuse disk of ring material—small dust particles, really. In spite of this conservative targeting strategy, the sensitive optical surfaces on Voyager's scan platform instruments (cameras, IRIS, PPS, and UVS) could still be abraded by these particles as they slam into Voyager at 25 km per second. The contingency measure taken to counteract this possibility is to point the instruments away from the incoming ring dust while Voyager passes through the closer, first ring-plane crossing.

To address the radiation hazard, special precautions are being taken. The spacecraft actually has two internal clocks—one in the FDS and one in the CCS. Each controls different types of sequence activities, but only the FDS can "fall behind" when given a dose of radiation. However, as some CCS events occur relative to FDS clock signals, it was decided to adopt two precautions. Key CCS events in CCS load B951 have been moved several seconds past the FDS "frame-start" signal, and a special onboard software routine has also been designed to "re-synchronize" the two clocks every now and then during the critical B951 near-encounter sequence.

For the atmospheric hazard, a conservative targeting strategy has been chosen as well: the planned path is expected to be at about 4400 km above the "detectable" atmosphere—albeit only 600 km beyond the reach of the nearest goblins able to cause some spacecraft problems even in the extremely rarefied outer fringes of Neptune's upper atmosphere. Nevertheless, for added protection near closest approach, Voyager's thrusters will be configured to push a bit harder each time they fire to enhance the craft's stability if it should be subjected to a small amount of atmospheric drag.

Even in the extreme case in which the atmosphere is found to extend farther out from Neptune than even our worst projections, something can be done to salvage the B951 science. If the larger atmosphere is detected early enough during approach, Voyager's path could actually be moved out from the preplanned trajectory with Trajectory Change Maneuver (TCM) B19 or TCM B20, and the B951 load could be updated to accommodate the small changes in instrument pointing and event timing induced by this deviation from the nominal plan. This clever contingency feature (which could also be used for ring-arc avoidance) is appropriately called the "mini-bailout" option.

The final environmental goblin, obscuration, is defeated very easily: instead of using the Sun or a star as its reference during these periods, Voyager 2 is configured to rely on its onboard gyroscopes and thrusters for attitude reference and control, eliminating the need altogether for tracking the Sun and stars.



SEIZURE OR DEGRADATION OF A SCAN PLATFORM ACTUATOR. The actuator that controls scan platform azimuth motion seized unexpectedly on Voyager 2 during the Saturn encounter. Though the performance for both actuators has been flawless since (following some diagnostic tests and implementation of special operating procedures), the project still considers this a plausible goblin, more so for the azimuth actuator than for elevation. Now the scan platform is treated with kid gloves, and all slewing activity is carefully planned and monitored. Slewing at the highest rate—which was the rate being used extensively before the seizure at Saturn—is now forbidden.

Periodic tests of actuator health, called Torque Margin Tests (TMTs), are performed to see if a goblin is lurking around the corner. The TMTs employ very short pulses of electrical current to nudge the actuator along while spacecraft specialists on Earth look for signs of excess friction or erratic motion. A period of science observation time in CCS load B921 has been earmarked for removal if analysts find evidence of actuator degradation and the project subsequently decides to perform a contingency TMT followed by healing exercises on the balky actuator.

For the azimuth actuator, an option exists to disable its slewing should it continue to perform poorly after the healing exercises, and then conduct the critical B951 load with elevation slewing only. For such a scenario, a special version of B951 that is compatible with elevation-only slewing has been created and will sit "on the shelf," ready to be used if this goblin strikes. This special version of B951 (referred to as R951 because the spacecraft must roll to compensate for the lack of azimuth motion) is the only special version of B951 for the Neptune encounter; at Uranus, three such loads were developed for the comparable high-value CCS load.

A MISSED MANEUVER. For a variety of reasons, it is possible (though very unlikely) to miss the preplanned execution of one of Voyager 2's critical approach trajectory correction maneuvers. In the case of TCM B18, a backup opportunity has been planned about one week after the nominal time. In fact, this period is essentially the same period of time mentioned above for the scan platform contingency window in B921. Either goblin is unlikely, and both appearing at the same time is highly unlikely. Thus, we can use the same window of time as a dual-purpose contingency slot without taking on unnecessary risk.

LOSS OF DIGITAL TAPE RECORDER. This piece of equipment has no backup on the Voyager spacecraft, so if it fails, all data recording capability would be lost. To insulate ourselves from the effects of such a goblin, a few things can be done. First, an appropriate mix of recorded and real-time (i.e., non-recorded, "live") data is planned, whenever possible. (This is not possible during the occultation periods, since direct communication with Earth is precluded when Voyager is behind Neptune or Triton.) Next, for many observations, more than the minimum desired amount of

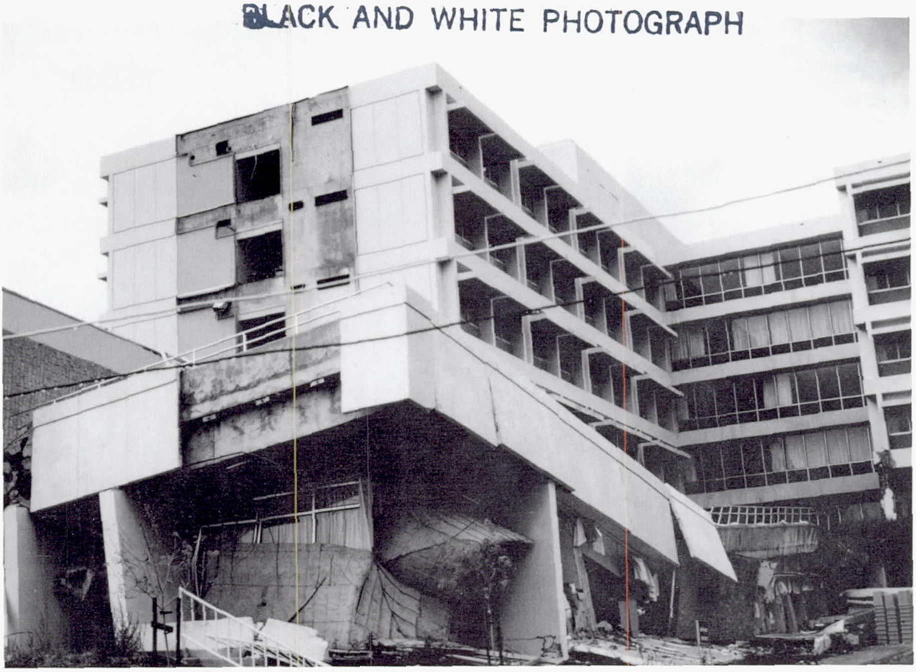


Figure 8-3. We don't expect a disaster (during the encounter period) like the San Fernando earthquake of 1971, but, with odds of 2 percent per year for a major quake in southern California, some contingency planning is wise. *(Courtesy of Caltech Earthquake Engineering Library.)*

data is planned into the sequence, so that if some are lost—for whatever reason—the scientists will still be happy. And, to accommodate a situation where bad weather on Earth engulfs the receiving DSN site, playback of the recorded data is backed up by a redundant playback, just in case the first is missed or degraded.

A MAJOR EARTHQUAKE IN CALIFORNIA. Yes, we even have plans for this goblin! The estimated probability of it poking its annoying nose in our business is 2 percent a year. If a major earthquake (or any other natural disaster, for that matter) should strike southern California, communications links between JPL and the remote DSN sites would most likely be disrupted for at least several hours to possibly many days. And if the encounter computer loads are not uplinked to Voyager in time, we're in big trouble. To ensure that this happens as scheduled for the most critical CCS load, a copy of the uplinkable series of 1s and 0s for this load will be stored on a special computer disk at each applicable DSN site, ready to be used for the uplink process if JPL is knocked out. The version of B951

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stored on the disk might be slightly out of date, but sending that to the spacecraft is far better than having nothing at all up there.

* * * *

Well, there you have it. We all hope—and yes, expect—that the encounter will proceed smoothly and, if history is any indicator, it will. Nevertheless, having a solid contingency plan in place still helps everyone think a little clearer and sleep a bit better.

THE ORIGINAL MURPHY'S LAW

In 1949, U.S. Air Force Captain Murphy (who keeps his first name secret to maintain some privacy) was in charge of a group seeking ways to increase the probability of a pilot surviving an aircraft crash through better seat design. Understanding how much of a deceleration the human body could withstand was one of the first tasks for the team. At the site of what is now Edwards Air Force Base in California, an officer-physician named Major John Stapp was acting as his own guinea pig by riding on a rocket sled at great speeds, followed by extremely fast stops. Captain Murphy supplied the critical deceleration sensors.

After some lower-speed preliminary trials, Major Stapp decided to take a risk and push the limits: he rode the sled up to 600 miles per hour, then came to a dead stop in less than two seconds, subjecting himself to a deceleration of over 40 times the normal force of gravity. He was left in pretty bad shape. What's worse, Murphy's sensors were installed in the only orientation of several that would lead to useless data, so Stapp had to do it again!

After Murphy realized what had happened, he looked at the Major and said, "If there are two or more ways to do something, and one of those ways can result in catastrophe, someone will do it." Stapp looked at Murphy and uttered, "That's Murphy's Law."

The next day at a press conference, Major Stapp altered Murphy's wording significantly, resulting in the more common version of Murphy's Law: If anything can go wrong, it will.

Murphy still likes his original version better ...

From an interview with Murphy in *The Beach Reporter*, Manhattan Beach, California, 1983 July 28, by Tom Adams.

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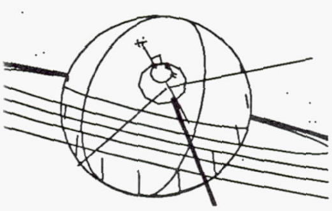


TO NEPTUNE: 99881 KM

Fortune sides with him who dares.

Virgil

9. ENGINEERING WIZARDRY

Imagine yourself at an international speedway watching a conference among designer, mechanic, and driver on how to win a long distance endurance race with a twelve-year-old racing car. Typically, the driver and other members of the team will brainstorm together in a cycle of design, test, and simulation to guarantee any projected new performance of their race car.

To have any hope of success against stiff odds, the team will try to invent new ways to squeeze extra performance out of their aging machine by the use of special engine tune-ups, new driving techniques, and by making special efforts to conserve fuel, tires, and other consumables to avoid frequent change-outs at the speedway pit stop.

The analogy of winning an international competition using an old racing car illustrates how the Voyager Flight Team has prepared for another race—to Neptune and beyond. The benefit of upgrading an aging (but well-designed) one-ton robot is to get a first-class look at the outermost giant planet of the solar system. Furthermore, this will be achieved at a modest additional cost beyond that spent for the primary Jupiter/Saturn and Uranus missions. When compared to the billion or so dollars that a newly designed outer planets mission would cost, not to mention the necessity of waiting well into the next century for results, the Voyager-2 mission to Neptune is a bargain!

While use of the international speedway's repair facilities allows our race-car team to update its old machine to compete in the race on Earth, the Voyager Flight Team cannot call the Voyager spacecraft back to Earth from its distant location. However, the Flight Team can reprogram Voyager's onboard computers to effect new strategies to win the race to Neptune and beyond. Reconfiguring the spacecraft's computer memories is somewhat analogous to choosing a new racing driver with more experience (i.e., with a better-performing brain and superior motor skills).

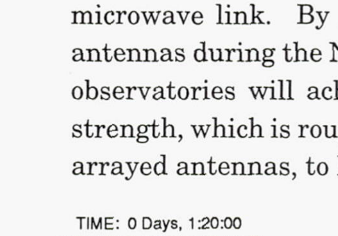
Maintaining a Strong Signal

With Neptune at nearly six times the Earth-to-Jupiter distance of 779 million km (483 million mi), the maximum data rate that can be received at Earth (and still just "hear" the signal above the noise level) would fall by a factor of nearly thirty-six (due to the square-of-distance penalty[1]) unless the Voyager Flight Team could pull some rabbits out of a hat.

At Jupiter's distance of five astronomical units (AU) the maximum data rate was 115,200 bits per second, at Saturn (10 AU) the maximum data rate was 44,800 bits per second, while at Uranus (19 AU) it was 29,900 bits per second. Plans for Neptune (30 AU) call for a maximum data rate of 21,600 bits per second. A major upgrade of the DSN's large antennas and the arraying of tracking antennas, as described below, allow us to arrest the natural fall of the signal strength to only half (rather than 1/9) that at Saturn when Voyager 2 reaches Neptune.

To meet the needs of Voyager at Neptune, as well as to enhance other future missions, the DSN undertook an ambitious program to convert its three large 64-m antennas to 70-m dishes. This was accomplished by tearing down and discarding all of the old metallic surface plates and structural outrigger beams, and then installing a totally new outer support structure along with precision surface plates that, once in place, could be adjusted to submillimeter accuracy. Holographic alignment techniques were introduced that permitted sharp focusing of the short wavelength (3-cm) radio signals. Together, the larger surface area and alignment and calibration techniques have yielded an improvement in signal strength of 55 percent for each 70-m antenna.

The Voyager Project has called upon additional resources beyond the NASA/JPL-operated DSN for data acquisition at the Neptune encounter. As was done for the Uranus encounter, the DSN is again teaming up with the Australian government's Parkes radio astronomy 64-m antenna operated by the Commonwealth Scientific and Industrial Research Organization (CSIRO). Three antennas (one 70-m and one 34-m) of the DSN facility in Canberra will combine signals (array) with the Parkes antenna via a 320-km (200-mi) microwave link. By simultaneously tracking Voyager from up to three antennas during the Neptune encounter period, the DSN and Parkes radio observatories will achieve a significant increase in the combined signal strength, which is roughly proportional to the combined surface areas of all arrayed antennas, to help defeat the square-of-distance penalty.



[1] A formula known as the inverse-square law is used to estimate the decrease in signal strength: radio signals weaken according to the ratio of the squares of the distances from the transmitter to the receiver. At the time of Jupiter flyby in 1979, for example, Jupiter was at about 5 AU, while Neptune will be at 30 AU. Therefore, $5^2/30^2 = (1/6)^2 = 1/36$. In other words, the signals received from Voyager 2 at Neptune will be about 36 times weaker than those that were received from the Voyagers at Jupiter.

However, by far the greatest signal strength improvement for Neptune will result from arraying the National Radio Astronomy Observatory's (NRAO) Very Large Array (VLA) antennas (twenty-seven 25-m dishes) near Socorro, New Mexico, with the Goldstone, California, DSN complex. The received signal power when the VLA is arrayed with a 70-m DSN antenna will be nearly three times greater than that received by the 70-m antenna by itself. Figure 9-1 shows a portion of the VLA antenna complex that heretofore has never been used for receiving telemetry data from an interplanetary spacecraft. Data will be relayed in real-time to the Goldstone site via a satellite microwave link between the VLA and the DSN.

Lastly, an additional enhancement has been made to the Neptune radio science experiment through a cooperative venture with the Japanese space agency permitting the use of their 64-m Usuda antenna on the day of encounter for the non-real-time combining of radio science data.

To take maximum advantage of these new signal reception capabilities, the onboard software in the Flight Data Subsystem (FDS) was completely

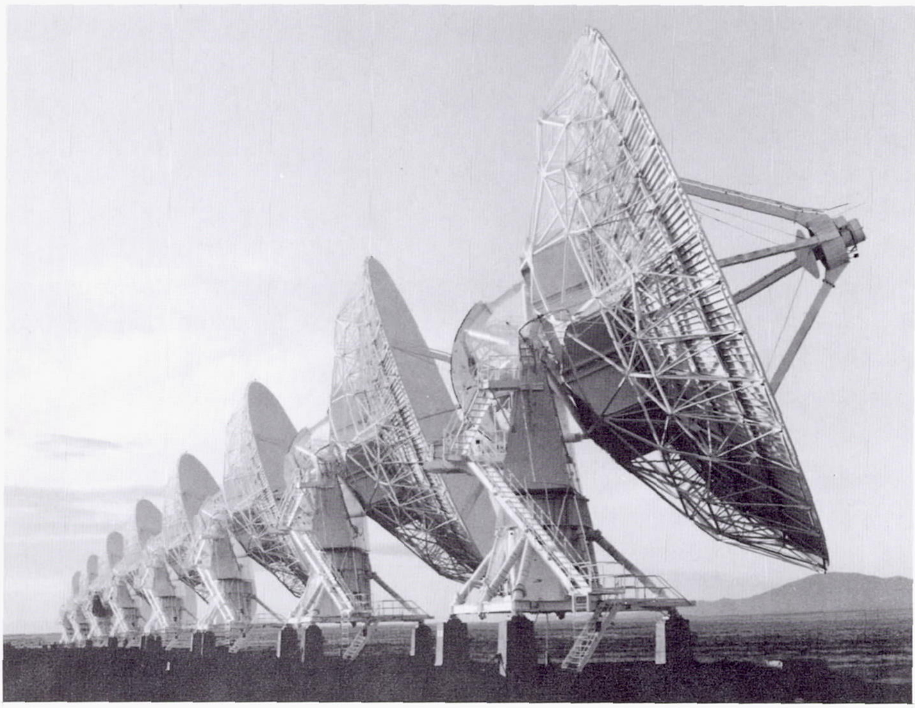


Figure 9-1. One of Voyager's new "hearing aids" consists of twenty-seven 25-m steerable radio antennas that form the Very Large Array located in the solitude of a New Mexico desert. These same antennas have been scanning the heavens, studying galactic radio sources, also listening intently for faint radio signals in the NRAO's Search for Extra-Terrestrial Intelligence (SETI) Program.

reprogrammed for more optimum data rates, data formats, and picture-editing capabilities.

Discarding Unnecessary Picture Data

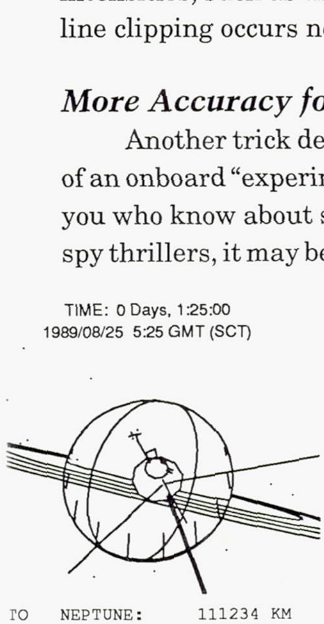
Neither the arraying of antennas over Australia nor the addition of the VLA to Goldstone's antennas can completely overcome the square-of-distance penalty. The Voyager Flight Team has therefore developed a clever scheme to pre-process the imaging data to reduce the total number of bits required to transmit a TV picture. This scheme was successfully introduced at Uranus encounter and will again be used at Neptune. They have used a special software routine known as Image Data Compression (IDC) in the onboard FDS backup computer, newly reconfigured for this task. JPL's own Robert F. Rice designed and developed the IDC technique.

Uncompressed Voyager TV images contain 800 lines, 800 dots (pixels) per line, and 8 bits per pixel (to express one of 256 gray levels). This means that every uncompressed TV image requires over five million bits. However, much of the information in a typical television image of a planetary system is frequently dark space or low-contrast cloud features. Therefore, by counting only the differences between adjacent pixel grey levels rather then the full 8-bit values, IDC can reduce by 60% or more the number of bits that characterize each image and thus reduce the time needed to transmit a complete TV image from Neptune to Earth.

As a rule, the reconstructed compressed image will be indistinguishable from the uncompressed image, as the IDC scheme loses no information for low-contrast scenes. Even for scenes with rapidly changing pixel intensities, such as the Saturn ring image shown in Figure 9-2, only minor line clipping occurs near the left- and right-hand edges of the frame.

More Accuracy for Fewer Bits

Another trick devised to beat the square-of-distance penalty is the use of an onboard "experimental" Reed-Solomon (RS) data encoder. For those of you who know about secret codes used to hide information in the context of spy thrillers, it may be reassuring to learn that there are also codes designed to preserve the "truth" of information. Data sent to the Earth pass through a plasma that may phase-modulate the signals with noise, i.e., turn a "correct" 0 bit into a "wrong" 1 bit, or vice versa.



Encoding these data has a price, and that paid for the old Golay encoding algorithm (used at Jupiter and Saturn) was one code bit overhead for every data

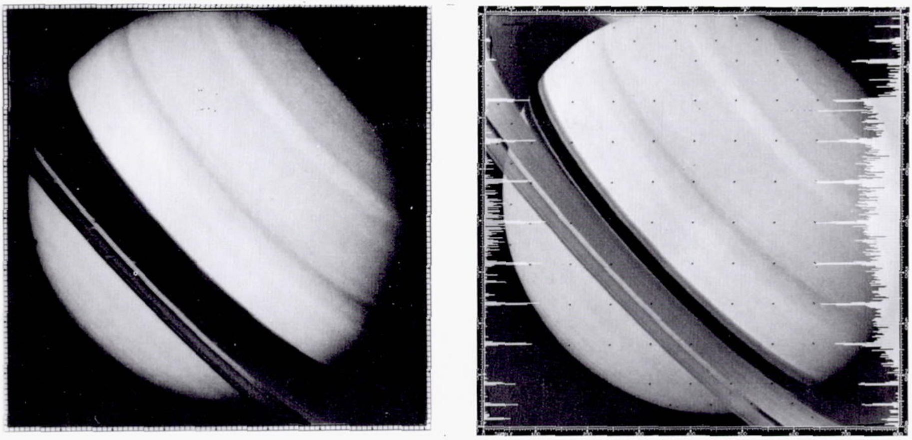


Figure 9-2. Each Voyager image at Jupiter and Saturn contained five million binary bits of data. To cope with the reduced data rates available from remote Uranus and Neptune, onboard data compression "differences" adjacent pixel brightness levels to return only two million bits per picture.

bit (100 percent). The new RS encoding scheme reduces this overhead to about 20 percent. In addition, it reduces the number of bit errors from 5 in 100,000 to only 1 in a million!

The field of information theory is much too esoteric for this Guide. Many have tried to approach C.E. Shannon's famous information capacity limit for a data channel. Figure 9-3 shows a rare gathering of four modern-day pioneers whose clever mathematical coding schemes have made important strides in efficient information transmission.

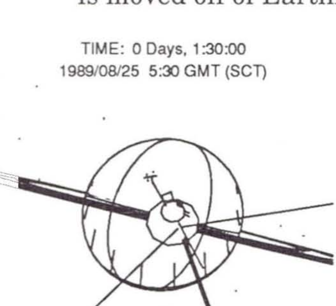
Taking Good Pictures in Feeble Light Levels

There is yet another penalty imposed on the Neptune encounter by the square-of-distance law. Reflected solar visual radiation from the Neptunian system is received by the spacecraft instruments at very reduced light levels (some 900 times fainter than at Earth). Thus, longer exposure times are required to gather the faint light, but this makes smear (picture-blurring) of rapidly moving targets, such as Triton or the Neptune ring-arcs, much more of a problem than it was at Jupiter, Saturn, or Uranus. The problem facing Voyager engineers is somewhat analogous to a situation confronting a photographer in a dimly lit room without a flash. To offset the required long exposure times, he must steady the camera on a tripod, use very sensitive film, or open the camera aperture. If the subject is moving, the photographer must smoothly pan the camera to "track" the target, much as a WWII tail gunner in a B17 had to do during combat missions.

Figure 9-3. The Uranus encounter in 1986 brought together four pioneers responsible for the NASA-standard Reed-Solomon/Viterbi coding system and the Rice data compression scheme. From left to right are Robert Rice of JPL, Andrew Viterbi of Qualcomm, Gustave Solomon of Hughes Aircraft Company, and Irving Reed of USC. (Photograph: Rick S. Austin.)

Once some preliminary estimates of required exposure times at Neptune had been calculated, the Project realized that neither the ground-based nor spacecraft-borne software programs were prepared to handle precise exposures beyond about 15 seconds. Therefore, a reprogramming and spacecraft testing effort was undertaken to provide a continuity of exposure times up to approximately one minute, as well as to permit multiples of 48-second increments beyond the original 0- to 15-second exposure interval.

For the Saturn and Uranus encounters, a technique was developed to use the spacecraft's gyroscopes to smoothly execute image motion compensation (IMC) turns to track selected targets during the near-encounter phase. Communications are broken off during IMC, since Voyager's antenna is moved off of Earthline, and all IMC data must be recorded.



A new capability termed nodding image motion compensation (NIMC) has been developed for the Neptune encounter. NIMC permits the spacecraft to remain nearly Earth-pointed while turning slightly, shuttering a frame, and turning back to Earth- point. This means the pictures can be transmitted directly

Figure 9-4. A WWII gunner had to slew his guns to track an enemy aircraft. In a similar manner, a photographer must pan his camera to avoid smeared pictures of moving subjects. *(Courtesy of the Boeing Company.)*

to the ground in real-time without the need for intermediate storage on the digital tape recorder (DTR). The nodding motion of the spacecraft is accurately controlled by precisely calibrating the small attitude-control thrusters, and then programming the onboard computer to fire the thrusters a predetermined number of times as needed to turn the spacecraft at the desired IMC rate. This is followed by a reset to the initial position in preparation for the next frame. Meanwhile, of course, the camera must be re-pointed between frames to account for the ever-changing target direction and spacecraft orientation.

Finally, as shown in Figure 9-5, another new capability planned for Neptune is called maneuverless image motion compensation (MIMC), whereby the scan platform itself is turned slowly (albeit somewhat jerkily because of the actuator design, which uses a stepper motor) relative to the spacecraft during an observation. Because of the unsteady turning motion, this panning technique has limited utility and is used only for first-order correction of rapidly moving targets that would otherwise appear hopelessly smeared. It was necessary to test a new scan platform turning rate for the sequencing process in order to obtain the proper MIMC rate for the chosen targets.

As Voyager cruises along in a zero-gravity environment, the start-stop motion of its tape recorder can add more jiggle to the spacecraft's natural limit cycle motion. To reduce these types of disturbances, the Voyager Flight Team has devised new software that fires the spacecraft thrusters to offset the tape recorder speed change whenever the tape recorder starts or stops. In addition, the pulse duration of the spacecraft's tiny attitude-control

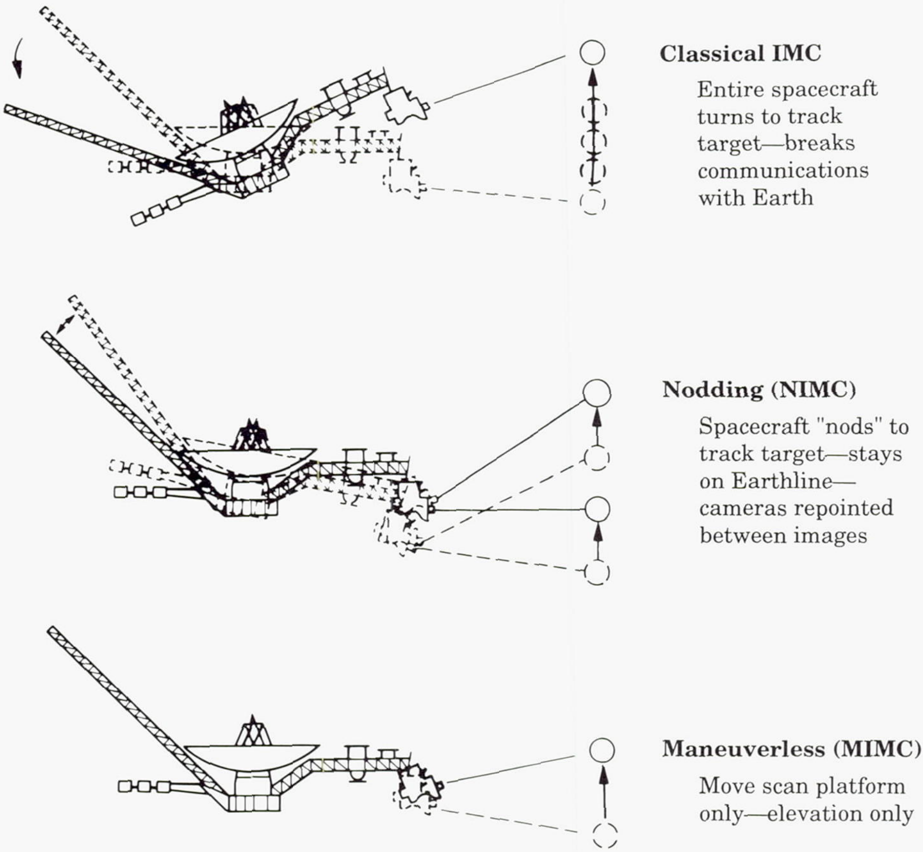
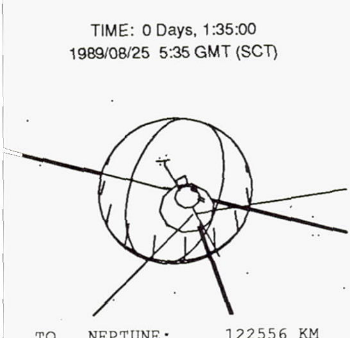


Figure 9-5. Who says you can't teach an old dog new tricks? To reduce picture smear when using long exposure times to handle the low light levels at Neptune, three different techniques have been developed to "track" the target.



thrusters has been reduced to provide a steadier spacecraft and thus decrease the number of blurred images.

Diagnosing the Health of the Actuators

Voyager 2 has performed remarkably well during the past twelve years, with only a few major hardware problems. For example, 102 minutes after Voyager 2 flew by Saturn closest approach on August 25, 1981, the scan platform stopped during a high-rate azimuth slew to a new target. This was believed to be due to a temporary seizure in the gear train of a small actuator (electric motor). Since that time, the Voyager Flight Team has devised a strategy to conserve platform usage and to operate the small drive actuators at lower speeds.

In addition, a clever method of checking the health of the platform actuators was developed to indirectly measure the amount of friction in the gear train. This Torque Margin Test (TMT) varies the duration or "width" of the electrical pulses to the stepper motor that drives the actuator gear train (see Figure 4-5). Even a healthy actuator would fail to move the platform if the stepper motor pulse width were reduced so low that it could not generate a minimum torque to overcome the normal frictional losses in the system.

The TMT strategy is to use these reduced pulse widths and note whether the platform slews at reduced or intermittent rates. The health of an actuator is gauged by the minimum pulse width required to slew the platform at the normally expected rate. An increase in this minimum pulse width may indicate degradation due to increased frictional losses from an unhealthy actuator. The TMT will be used during the Neptune encounter period to monitor the actuator's performance (see Chapters 6 and 8).

Faster Response From the "Old" Robot

Since Saturn, the Voyager engineers have also added a new capability to perform higher-rate spacecraft turns about the roll axis in time-critical periods of the encounter. This capability to roll at 0.3 deg/sec may be used to conserve the worrisome actuator gears by selectively substituting spacecraft roll maneuvers for scan platform azimuth movement, and to prepare for a contingency backup in the remote possibility of another scan platform anomaly.

The Voyager engineers, knowing that the previous gyro-controlled IMC maximum rates were too slow to track the moon Miranda during the mad dash past Uranus, reprogrammed the onboard computers to overcome this hurdle. Instead of the former capability (at Saturn) of 70 deg/h (the sum of all three axis rates), Voyager will be able to perform gyro-drift turns as fast as 120 deg/h for each axis, simultaneously. Because of this, we are looking for some nice, sharp images of Triton.

Big Changes in the Deep Space Network

Waiting to capture the Voyager data from Neptune will be the multi-million-dollar Mark IVA configuration of the Deep Space Network, as developed for the Uranus encounter. Nine DSN antennas, located in three Deep Space Communications Complexes (DSCCs) around the world, are scheduled to be controlled and operated according to an advanced concept of command, communications, and control (C^3) that uses new microprocessors and software distributed over a Local Area Network (LAN).

Each individual antenna and its co-located electronics will operate unattended except for maintenance. A Complex Monitor Control (CMC) operator configures electronic resources, located in the new Signal Processing Center (SPC) at each complex, for each antenna at the complex. No longer will each antenna individually require a complete set of dedicated electronics to fulfill downlink telemetry, command, ranging, or long-baseline navigation functions.

Another recent capability is that faulty equipment should be quickly replaced by the CMC operator if required, thus preserving vital science data during critical moments of the encounter. Like any new large and complex system implementation, the Mark IVA has had its teething problems, but they were resolved by the start of the Uranus encounter.

Each flight project such as Voyager will be assigned to one or more Link Monitor Control (LMC) console operators. While the CMC operator configures the electronics for each antenna to support a particular schedule, the LMC operator (see Figure 9-6) assures the required data processing support for individual spacecraft, and controls antenna performance via the LAN. Typically, one LMC operator is available for each antenna at a complex.

The "arraying" of antennas is a scheme whereby all antennas receive the Voyager signals, and the separate subcarrier signals are combined to achieve a greater signal-to-noise ratio (SNR). This Mark IVA capability to array antennas for additional SNR is, of course, vital to the success of the Voyager encounter at Neptune.

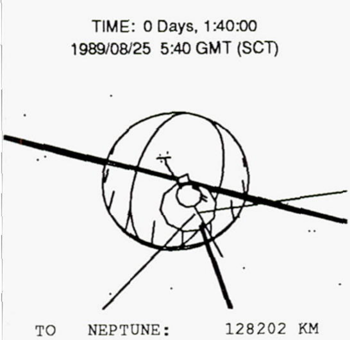
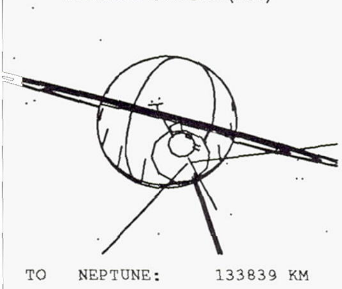


Figure 9-6. Not to be forgotten are the dedicated efforts of DSN personnel at remote locations. The Link Monitor Control operators, shown above at the Madrid DSCC, are vital in capturing, saving, and relaying scientific data back to JPL.

The Bottom Line

This overview provides some idea of why the Voyager Flight Team hopes to win the race to Neptune and beyond: because it, JPL, and NASA are determined to provide, at minimum cost, a manyfold increase in the science knowledge of this giant planet by continually upgrading the capabilities of the aging Voyager spacecraft and the supporting facilities at Earth Base.


TIME: 0 Days, 1:45:00
1989/08/25 5:45 GMT (SCT)
TO NEPTUNE: 133839 KM

The disposition of a fly's wings or of the feelers of a snail is sufficient to confound you.

Voltaire

10. GEE-WHIZ FACTS

The Voyager mission was officially approved in May 1972, has received the dedicated efforts of many skilled personnel for nearly two decades, and has returned more new knowledge about the outer planets than had existed in all of the preceding history of astronomy and planetary science. And the two Voyager machines are still performing like champs.

It must come as no surprise that there are many remarkable, "gee-whiz" facts associated with the various aspects of the Voyager mission. These tidbits have been summarized in this chapter in appropriate categories. Several may seem difficult to believe, but they are all true and accurate.

Overall Mission

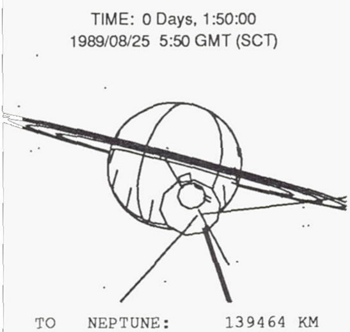
1. The total cost of the Voyager mission from May 1972 through the Neptune encounter (including launch vehicles, nuclear-power-source RTGs, and DSN tracking support) is 865 million dollars. At first, this may sound very expensive, but the fantastic returns are a bargain when we place the costs in the proper perspective. It is important to realize that:
   (a) on a per-capita basis, this is only 20 cents per U.S. resident per year, or roughly half the cost of one candy bar each year since project inception.
   (b) the daily interest on the U.S. national debt is a major fraction of the entire cost of Voyager.
2. A total of 11,000 workyears will have been devoted to the Voyager project through the Neptune encounter. This is equivalent to one-third the amount of effort estimated to complete the great pyramid at Giza to King Cheops.
3. A total of five trillion bits of scientific data will have been returned to Earth by both Voyager spacecraft at the completion of the Neptune encounter. This represents enough bits to encode over 6000 complete sets of the Encyclopedia Brittanica, and is equivalent to about 1000 bits of information provided to each person on Earth.

Figure 10-1. On a U.S. resident per-capita basis, Voyager is a remarkable bargain at 20 cents per year.

4. The sensitivity of our deep-space tracking antennas located around the world is truly amazing. The antennas must capture Voyager information from a signal so weak that the power striking the antenna is only 10^{-16} watts (1 part in 10 quadrillion). A modern-day electronic digital watch operates at a power level 20 billion times greater than this feeble level.

Voyager Spacecraft

1. Each Voyager spacecraft comprises 65,000 individual parts. Many of these parts have a large number of "equivalent" smaller parts such as transistors. One computer memory alone contains over one million equivalent electronic parts, with each spacecraft containing some five million equivalent parts. Since a color TV set contains about 2500 equivalent parts, each Voyager has the equivalent electronic circuit complexity of some 2000 color TV sets.



2. Like the HAL computer aboard the ship Discovery from the famous science fiction story *2001: A Space Odyssey*, each Voyager is equipped with computer programming for autonomous fault protection. The Voyager system is one of the most sophisticated ever designed for a deep-

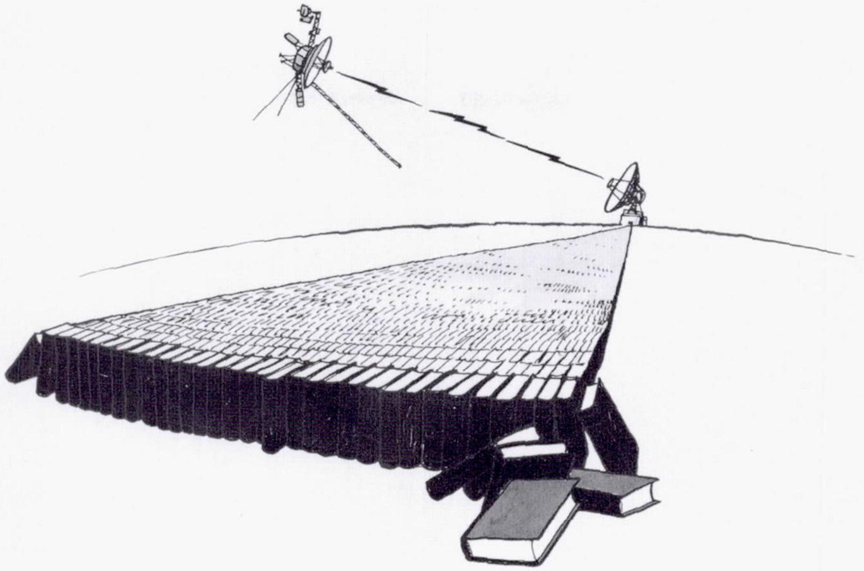


Figure 10-2. Both Voyagers have returned five trillion bits of science data since launch, equivalent in information bits to that needed to encode 6000 sets of the Encyclopedia Brittanica.

space probe. There are seven top-level fault protection routines, each capable of covering a multitude of possible failures. The spacecraft can place itself in a safe state in a matter of only seconds or minutes, an ability that is critical for its survival when round-trip communication times from Earth stretch to several hours as the spacecraft journeys to the remote outer solar system.

3. Both Voyagers were specifically designed and protected to withstand the large radiation dosage during the Jupiter swing-by. This was accomplished by selecting radiation-hardened parts and by shielding very sensitive parts. An unprotected human passenger riding aboard Voyager 1 during its Jupiter encounter would have received a radiation dose equal to one thousand times the lethal level.

4. The Voyager spacecraft can point its scientific instruments on the scan platform to an accuracy of better than one-tenth of a degree. This is comparable to bowling strike-after-strike *ad infinitum*, assuming that you must hit within one inch of the strike pocket every time. Such precision is necessary to properly center the narrow-angle picture

whose square field-of-view would be equivalent to the width of a bowling pin.

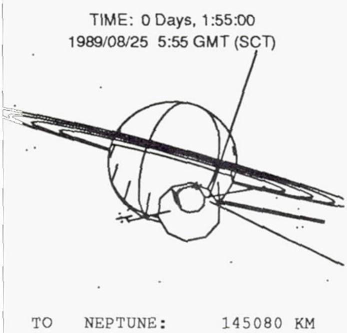
5. To avoid smearing in Voyager's television pictures, spacecraft angular rates must be extremely small to hold the cameras as steady as possible during the exposure time. Each spacecraft is so steady that angular rates are typically 15 times slower than the motion of a clock's hour hand. But even this will not be quite steady enough at Neptune, where light levels are 900 times fainter than those on Earth. Spacecraft engineers have already devised ways to make Voyager 30 times steadier than the hour hand on a clock.

6. The electronics and heaters aboard each nearly one-ton Voyager spacecraft can operate on only 400 watts of power, or roughly one-fourth that used by an average residential home in the western United States.

7. A set of small thrusters provides Voyager with the capability for attitude control and trajectory correction. Each of these tiny assemblies has a thrust of only three ounces. In the absence of friction, on a level road, it would take nearly six hours to accelerate a large car up to a speed of 48 km/h (30 mph) using one of these thrusters.

8. The Voyager scan platform can be moved about two axes of rotation. A thumb-sized motor in the gear train drive assembly (which turns 9000 revolutions for each single revolution of the scan platform) will have rotated five million revolutions from launch through the Neptune encounter. This is equivalent to the number of automobile crankshaft revolutions during a trip of 2725 km (1700 mi).

9. The Voyager gyroscopes can detect spacecraft angular motion as little as one ten-thousandth of a degree. The Sun's apparent motion in our sky moves over 40 times that amount in just one second.



10. The tape recorder aboard each Voyager has been designed to record and playback a great deal of scientific data. The tape head should not begin to wear out until the tape has been moved back and forth through a distance comparable to that across the United States. Imagine playing

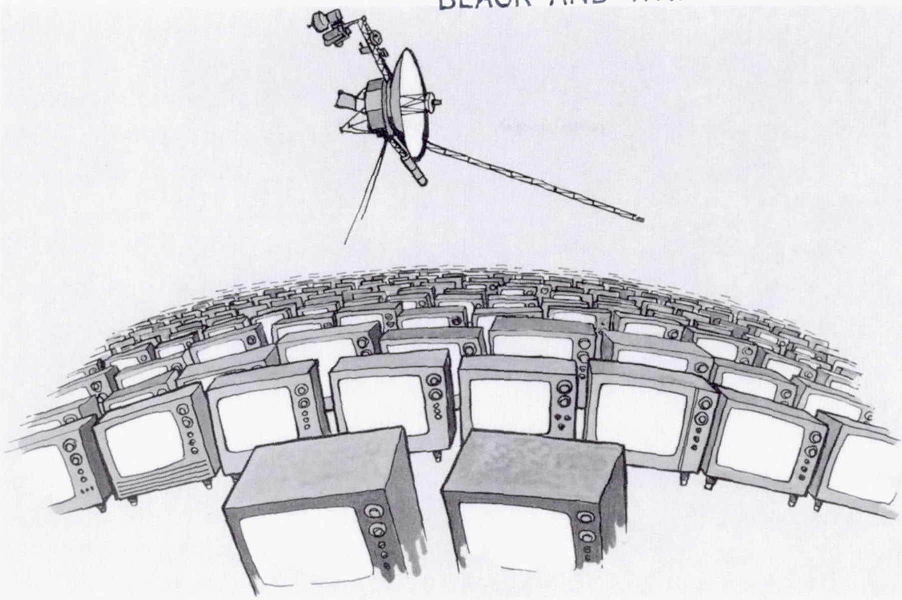


Figure 10-3. Each Voyager spacecraft consists of about 5,000,000 equivalent electronic parts—comparable to some 2000 color TV sets.

a two-hour video cassette on your home VCR once a day for the next 22 years, without a failure.

11. The Voyager magnetometers are mounted on a frail, spindly, fiberglass boom that was unfurled from a two-foot-long can shortly after the spacecraft left Earth. After the boom telescoped and rotated out of the can to an extension of nearly 13 meters (43 feet), the orientations of the magnetometer sensors were controlled to an accuracy better than two degrees.

Navigation

1. Each Voyager used the enormous gravity field of Jupiter to be hurled on to Saturn, experiencing a Sun-relative speed increase of roughly 35,700 mph. As total energy within the solar system must be conserved, Jupiter was initially slowed in its solar orbit—but by only one foot per trillion years. Additional gravity-assist swing-bys of Saturn and Uranus were necessary for Voyager 2 to complete its Grand Tour flight to Neptune, reducing the trip time by nearly twenty years when compared to the unassisted Earth-to-Neptune route.

2. The Voyager delivery accuracy at Neptune of 100 km (62 miles), divided by the trip distance or arc length traveled of 7,128,603,456 km (4,429,508,700 mi), is equivalent to the feat of sinking a 3630-km (2260-mi) golf putt, assuming that the golfer can make a few illegal fine adjustments while the ball is rolling across this incredibly long green.

3. Voyager's fuel efficiency (in terms of mpg) is quite impressive. Even though most of the launch vehicle's 700-ton weight is due to rocket fuel, Voyager 2's great travel distance of 7.1 billion km (4.4 billion mi) from launch to Neptune results in a fuel economy of about 13,000 km per liter (30,000 mi per gallon). As Voyager 2 streaks by Neptune and coasts out of the solar system, this economy will get better and better!

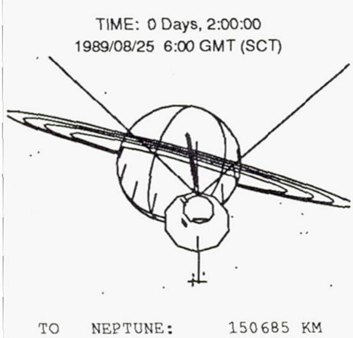
Science

1. The resolution of the Voyager narrow-angle television cameras is sharp enough to read a newspaper headline at a distance of 1 km (0.62 mi).

2. Pele, the largest of the volcanos seen on Jupiter's moon Io, is throwing sulfur and sulfur-dioxide products to heights 30 times that of Mount Everest, and the fallout zone covers an area the size of France. The eruption of Mount St. Helens was but a tiny hiccup in comparison (admittedly, Io's surface-level gravity is some six times weaker than that of Earth).

3. The smooth water-ice surface of Jupiter's moon Europa may hide an ocean beneath, but some scientists believe any past oceans have turned to slush or ice. In *2010: Odyssey Two*, Arthur C. Clarke wraps his story around the possibility of life developing within the oceans of Europa.

4. The rings of Saturn appeared to the Voyagers as a dazzling necklace of 10,000 strands. Trillions of ice particles and car-sized bergs race along each of the million-kilometer-long tracks, with the traffic flow orchestrated by the combined gravitational tugs of Saturn, a retinue of moons and moonlets, and even nearby ring particles. The rings of Saturn are so thin in proportion to their 171,000-km (106,000-mi) width that, if a full-scale model were to be built with the thickness of a phonograph record,



TO NEPTUNE: 150685 KM

the model would have to measure four miles from its inner edge to its outer rim. An intricate tapestry of ring-particle patterns is created by many complex dynamic interactions that have spawned new theories of wave and particle motion.

5. Saturn's largest moon Titan was seen as a strange world with its dense atmosphere and variety of hydrocarbons that slowly fall upon seas of ethane and methane. To some scientists, Titan, with its principally nitrogen atmosphere, seemed like a small Earth whose evolution had long ago been halted by the arrival of its ice age, perhaps deep-freezing a few organic relics beneath its present surface.

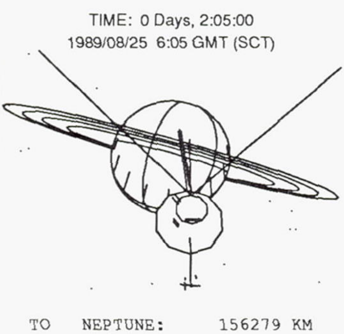
6. The rings of Uranus are so dark that Voyager's challenge of taking their picture was comparable to the task of photographing a pile of charcoal briquettes at the foot of a Christmas tree, illuminated only by a 1-watt bulb at the top of the tree, using ASA-64 film. And Neptune light levels will be less than half those at Uranus.

The Future

1. The solar system does not end at the orbit of Pluto, the ninth planet. Nor does it end at the heliopause boundary, where the solar wind can no longer continue to expand outward against the interstellar wind. It extends over a thousand times farther out where a swarm of small cometary nuclei, termed Oort's Cloud, is barely held in orbit by the Sun's gravity, feeble at such a great distance. Voyager 1 passed above the orbit of Pluto in May 1988, and Voyager 2 will pass beneath Pluto's orbit in August 1990. But even at speeds of over 35,000 mph, it will take nearly 20,000 years for the Voyagers to reach the middle of the comet swarm, and possibly twice this long for them to pass the outer boundaries of cometary space. By this time, they will have traveled a distance of two light-years, equivalent to half of the distance to Proxima Centauri, the nearest star.

2. Barring any serious spacecraft subsystem failures, the Voyagers may survive until the early twenty-first century, when diminishing power and hydrazine levels will prevent further operation. Were it not for these dwindling consumables and the possibility of losing lock on the faint Sun, our tracking antennas could continue to "talk" with the Voyagers for another century or two! See Table 12-1 for a listing of lifetime limiting factors.

Don't forget to see Chapter 12 for more amazing facts about the flights of the two Voyager spacecraft as they silently coast towards other stars several millennia into the future.



Are thy wings plumed indeed for such far flights?
Walt Whitman

11. HOW FAR AND HOW FAST

Prepare yourself to enter into a new realm of distance, speed, and time as measured by the journeys of the Voyager spacecraft. Here you do not think in terms of the units used for an automobile trip, say from Los Angeles to New York, a distance of 2800 miles with a driving time of 56 hours at an average speed of 50 mph. But rather we will use metric units. Thus, the same road trip becomes 4500 kilometers at a speed of 80 km/h. More importantly though, you must vastly expand the distance dimensions used to measure the flights of spacecraft that have trip durations of many years.

Because of the large distances between planetary bodies, it is usually convenient to express these distances in terms of Astronomical Units (AU), where 1 AU is defined as the mean distance of the Earth from the Sun and equals 149,600,000 kilometers (or about 93 million miles). To put this distance into proper perspective, consider the fact that it would take you 212 years of nonstop driving at 80 km/h (50 mph) to travel just 1 AU. Even a supersonic transport traveling at Mach 2.5 (1900 mph) would take almost 6 years nonstop.

The Grand Tour

Figure 11-1 shows the paths followed by the two Voyager spacecraft, as well as by Pioneers 10 and 11, as they spiral outward from their Earth-launch points. Both Voyagers have had close encounters with Jupiter and Saturn, but only Voyager 2 continued on to Uranus and Neptune. This occurred for two reasons. First, the unique "Grand Tour" alignment of Earth, Jupiter, Saturn, Uranus, and Neptune occurs for only three consecutive launch years out of every 176 years, and 1977 was one of those golden planetary moments. And second, Voyager 1 arrived at Saturn first and successfully scanned the top-priority moon Titan, freeing the later-arriving Voyager 2 from the Titan obligation, thereby allowing it to be targeted on to Uranus and Neptune.

The Voyager spacecraft were both launched in 1977, and the Pioneer 10 and 11 spacecraft were launched in 1972 and 1973, respectively. These four spacecraft are the very first that will escape the gravity of our solar system as they continue their unending journeys into the Milky Way galaxy at speeds of "only" a few AU per year. For Voyager 1, the 3.5 AU/yr departure

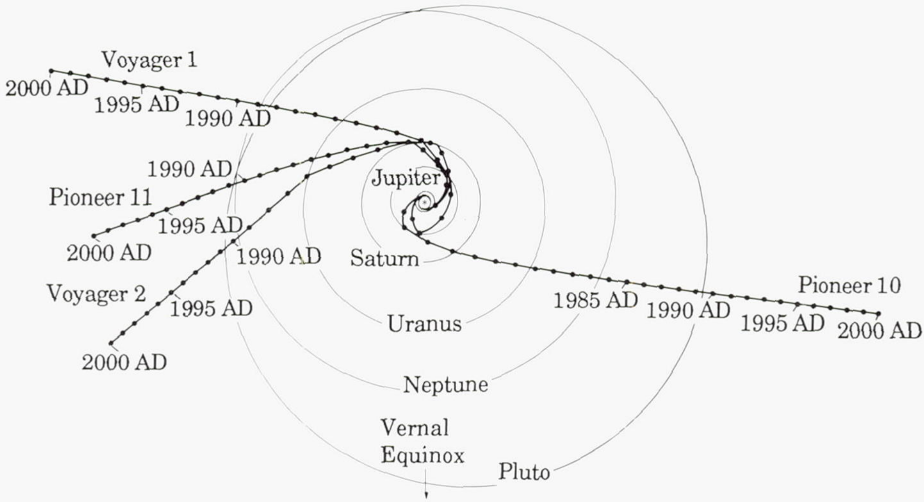
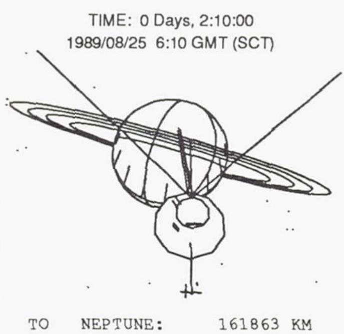


Figure 11-1. This is an ecliptic plane projection of the Voyager and Pioneer flight paths. All will escape from the solar system, but the faster-moving Voyagers will win the race. Planet and spacecraft positions are shown in 2000 A.D.

speed is nearly 60,000 km/h (37,200 mph), while for Voyager 2 the departure speed is just overt 53,400 km/h (33,100 mph). Although this may seem fast by terrestrial standards, you'll soon realize that it is excruciatingly slow by interstellar standards. If you want a little rule for estimating how far the Voyagers will be from our Sun in some future year, use 76.34 + 3.50 (Year - 2000) for Voyager 1 and 59.75 + 3.13 (Year - 2000) for Voyager 2 . . . and you'll have the approximate distance in AU.

Figure 11-2 presents a three-dimensional view of the Voyager spacecraft trajectories. As a consequence of encountering Titan prior to Saturn closest approach, Voyager 1 passed somewhat "beneath" Saturn, being deflected upwards, north of the ecliptic plane at an angle of about 35 degrees.

After the Neptune encounter, Voyager 2 will depart south of the ecliptic plane at an angle of approximately 48 degrees. This departure condition results from Project plans to obtain a 40,000 km (25,000 mi) flyby of the satellite Triton after skimming over the northern polar regions of Neptune (being deflected downward) at an altitude of just 4850 km (3010 mi) above the cloud tops (100 millibars).



The Great Escape

From Figure 11-1 it can be seen that Pioneer 10 has a head start on the other spacecraft, having passed the orbit of Neptune in 1985 at a solar radius

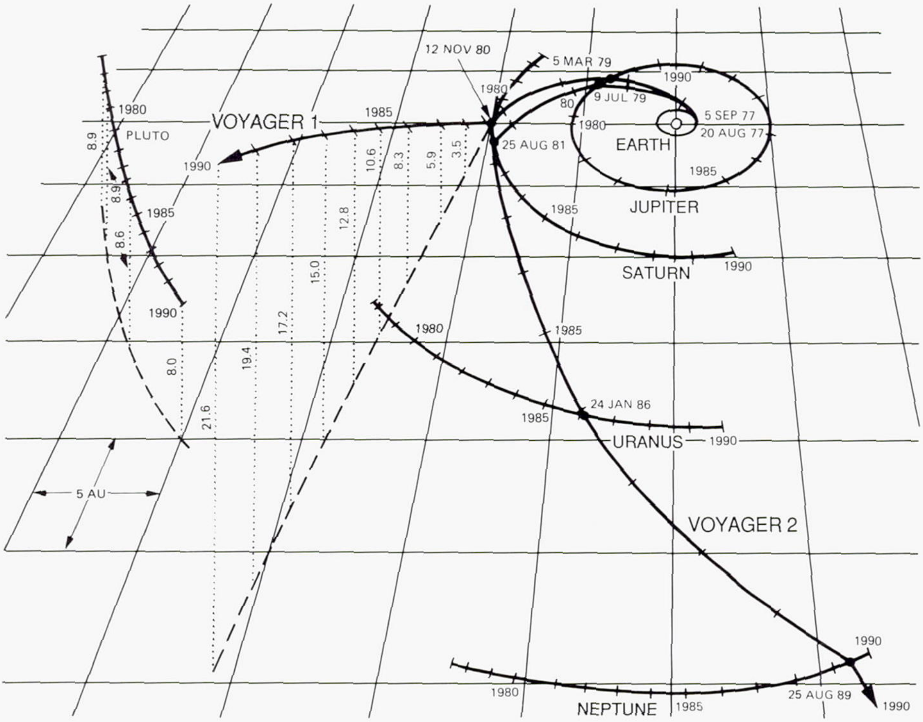


Figure 11-2. Gravity assist has deflected the two Voyagers out of the ecliptic plane. Flying "under" Saturn, Voyager 1 was lofted above the ecliptic at a 35° angle.

of 30 AU. However, Voyager 1 was the first to cross over Pluto's eccentric inclined orbit in 1988, at a distance of about 29 AU, when Pluto's orbit was inside that of Neptune's. Pioneer 11 crossed over the Uranian orbit slightly before Voyager 2's 1986 encounter, but Voyager 2 will be the first to reach (and encounter) Neptune. Because of the significant speed advantage of the two Voyager spacecraft, they will gradually out-distance the Pioneers in the twenty-first century.

A very challenging future goal is for the Voyager Project to reach the heliopause boundary (see Figure 12-1) with spacecraft that are operational at a distance of 50 to 150 AU.

However, the spacecraft won't have enough power to operate much beyond the year 2017, when Voyagers 1 and 2 will be at distances from the Sun of 138 AU and 113 AU, respectively. Far beyond the heliopause, at the very edge of our solar system, the Voyagers will pass through Oort's Cloud of cometary nuclei. However, at the cloud's great distance of at least 63,000 AU (about 1 light-year), the Voyagers will not arrive for another 20,000 years.

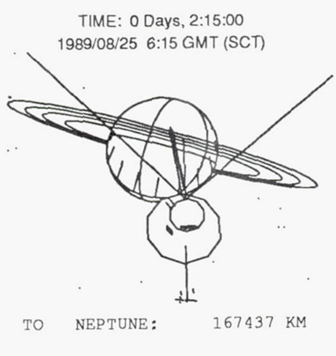
Voyager 2 at Neptune

Relative to an observer on Neptune, Voyager 2 is approaching from generally the Sun's direction at a speed of about 60,000 km/h (37,500 mph). Meanwhile, Neptune is orbiting the Sun at a mean radius of 30 AU with a speed in excess of 19,500 km/h (12,100 mph), but the giant planet still takes 165 years to complete just one orbit. (Neptune has not completed one orbit since its discovery 143 years ago!) By the Neptune closest approach time of 04:00 GMT on August 25, 1989, the spacecraft will have travelled a distance of more than 47 AU (4,359,300,000 mi) along its heliocentric path since leaving Earth 12 years earlier.

Neptune is truly a giant planet, with a diameter of 49,600 km (30,800 mi), compared to Earth at 12,800 km (7,900 mi). Neptune is nearly four times the diameter of Earth and 57 times larger in volume than Earth. It is significant to note that the path of Voyager 2 must pass within 4850 km of the cloud tops of Neptune in order to provide the proper gravitational deflection to pass close to Triton.

Another interesting view of the Neptune encounter is shown in Figure 6-1, showing north polar passage of Neptune by the spacecraft, followed by both Earth and solar occultations by Neptune and any existing rings. At the time of closest approach, a radio signal being sent from the spacecraft to Earth will take 4 hours and 6 minutes to reach Earth. This means the data transmitted at the time of closest approach will be seen back on Earth at 08:06 GMT or 1:06 AM PDT, Friday, August 25, 1989. The most intense time for media coverage will run from about 12 hours before to 50 hours after Neptune closest approach (allowing for recorder playbacks).

There are just two known satellites of Neptune. Triton, the larger, has an estimated diameter of 3000 km (1860 miles), nearly 500 km smaller than Earth's Moon. Triton's exact size is very uncertain, however, and could be as small as 2200 km (1360 mi), or as large as 5000 km (3100 mi). Triton revolves in a retrograde direction around Neptune once every 5.9 days, in an orbit inclined about 20° to Neptune's equatorial plane. Triton travels at a speed of about 15,800 km/h (9800 mph), relative to Neptune, in its orbit about the gas giant.



The smaller satellite, Nereid, has an estimated diameter of 800 km (500 mi). Nereid takes 360 days (about one year) to revolve around Neptune, in an orbit inclined 30° to Neptune's equator, at a speed of about 4000 km/h (2500 mph) relative to Neptune. Nereid's orbit is highly eccentric, so its distance from Neptune varies greatly. Its semi-major axis is

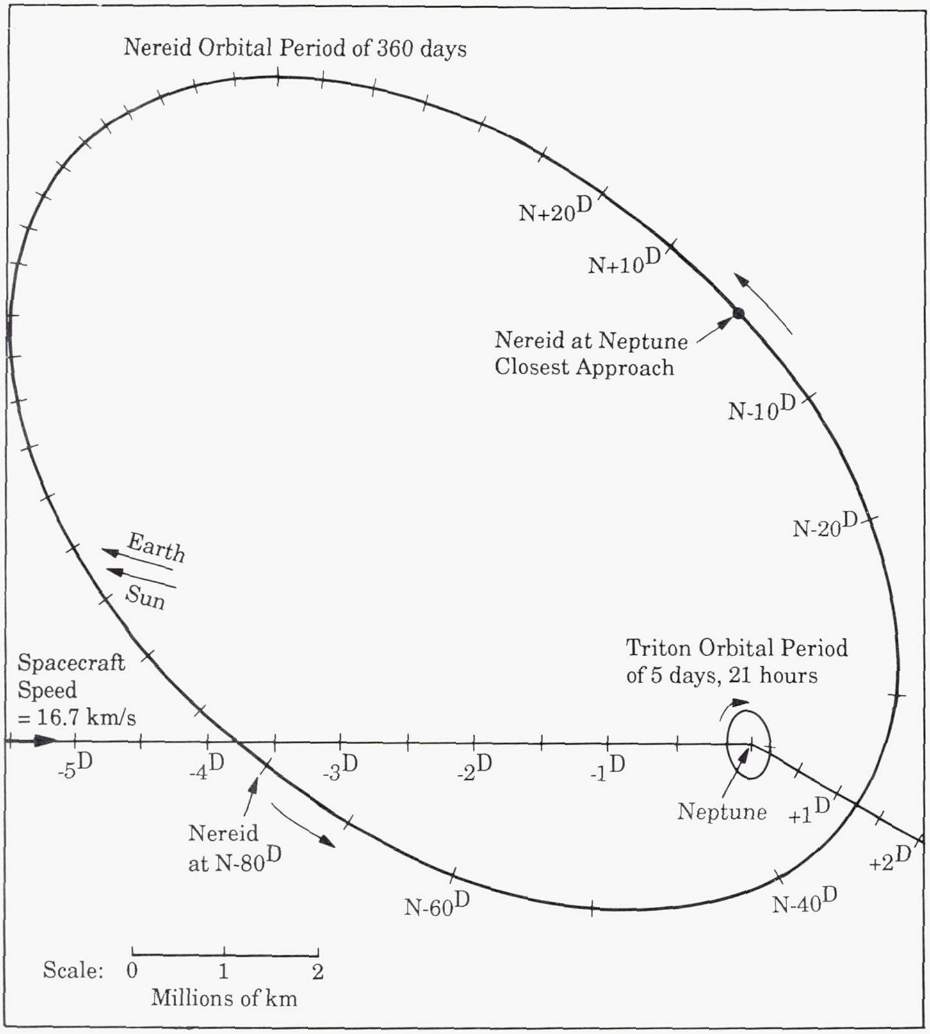


Figure 11-3. Voyager 2 comes no closer than about 4.6 million km (2.9 million mi) to Nereid.

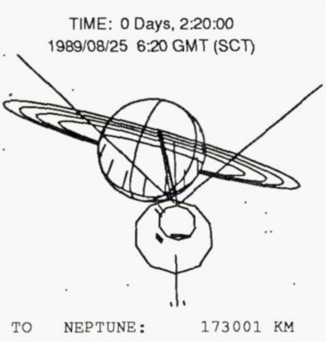
5,510,000 km, or 14 times the distance from the Earth to the Moon (see Figure 11-3).

Key Events, Distances, and Speeds

Table 11-1 provides a list of trajectory events during the Voyager-2 approach and encounter with Neptune, including a few key science links (see also the end of Chapter 2, portions of Chapter 6, and the acronym short descriptions in Chapter 19) as well. The times shown for the latter refer to the link start times.

Table 11-1. Neptune Encounter Trajectory Events

Event	Event Time (GMT)	Time from Neptune Closest Approach (dd/hh:mm)	Distance (km) (from center of event body)
Start Observatory Phase	6/05/89 06:42	-80/21:18	
TCMB18	8/01/89 19:56	-23/16:04	
Start Far-Encounter Phase	8/06/89 08:42	-18/19:18	
TCMB19	8/15/89 09:42	-09/18:18	
TCMB20	8/21/89 11:09	-03/16:51	
Start Near-Encounter Phase		-00/12:17	
Nereid best imaging		-00/11:20	
Triton longitudinal imaging		-00/10:39	
20 Neptune radii+	8/24/89 20:37	-00/07:23	495,620
Search for ring arcs		-00/07:16	
Uplink Late Stored Update		-00/06:00	
Ring occultation of Sigma-Sagittarii		-00/05:01	
Nereid closest approach	8/25/89 00:23	-00/03:37	4,638,180
10 Neptune radii	00:30	-00/03:30	247,810
Triton longitudinal imaging		-00/02:55	
Ascending node	03:03	-00/00:57	78,717
Roll spacecraft to +61 deg.		-00/00:56	
Neptune closest approach**	04:00	00/00:00	29,183
Enter Neptune umbra (Sun occultation)	04:06	+00/00:06	30,283
Enter Neptune Earth occultation	04:06	+00/00:06	30,453
Start limbtrack maneuver		+00/00:06	
Exit Neptune Earth occultation	04:55	+00/00:55	76,844
Exit Neptune umbra (Sun occultation)	04:56	+00/00:56	77,732
Descending node	05:29	+00/01:29	115,159
End limbtrack maneuver		+00/01:30	
Roll spacecraft to Alkaid		+00/01:50	
Triton imaging (VTCOLOR)		+00/02:05	
Triton mapping (VTMAP)		+00/02:34	
10 Neptune radii	07:30	+00/03:30	247,810
Triton highest resolution (VTERM)		+00/04:40	
Triton occults ß Canis Majoris	09:13	+00/05:13	40,020
Triton closest approach	09:14	+00/05:14	39,981
Enter Triton Earth occultation++	09:44	+00/05:44	51,023
Enter Triton Sun occultation	09:44	+00/05:44	51,185
Exit Triton Earth occultation	09:47	+00/05:47	53,313
Exit Triton Sun occultation	09:47	+00/05:47	53,357
Roll spacecraft to Canopus		+00/06:04	
Triton crescent imaging		+00/06:17	
20 Neptune radii	11:23	+00/07:23	495,620
Start Post-Encounter Phase		+04/16:42	
End Post-Encounter Phase		+38/07:42	



* Times given are the nominal start times and may vary by a few minutes due to ongoing updates.

**One-way light time is 246 minutes at Neptune closest approach.

\+ Assumes a 100 mbar equatorial radius value of 24,781 km.

++Assumes Triton radius of 1500 km for Sun and Earth occultations.

Finally, many news people like to know spacecraft distance (how far) and speed (how fast) at almost any time the urge strikes them to want these facts. For "8-place precision," the Voyager Navigation Team must be consulted and, of course, the requester must specify the "relative-to" body for distance or speed.

However, for those who would be content with approximate values, they may find Figures 11-4 and 11-5 quite useful. After all, in the time it takes to say "Voyager 2 is four billion, four hundred and twenty-four million, nine hundred and forty-four thousand, six hundred and eighty kilometers from Earth," the spacecraft has moved 160 km (100 mi) and Earth has moved 300 km (185 mi)! And, if the listener wants to repeat back the number for verification, well . . . you get the idea.

Finally, Figure 11-6 illustrates the speed of Voyager 2 (relative to the Sun) as it leaves the already fast-moving Earth, picks up gravity-assist (see Chapter 7) speed gains from Jupiter, Saturn, and Uranus, loses a little speed by passing Neptune slightly on its leading hemisphere, and heads on out of the solar system on its escape trajectory. The massive Sun, though pulling back on the spacecraft, cannot slow Voyager's speed enough to prevent the craft's escape.

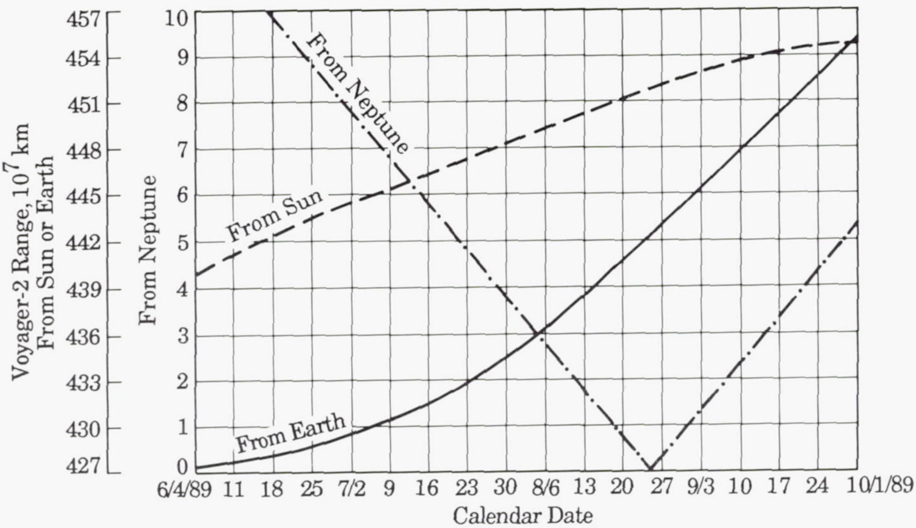


Figure 11-4. These ranges should be accurate enough for most information purposes. In fact, in the time it takes to quote an "eight-place" figure, all of the bodies have moved a few hundred kilometers.

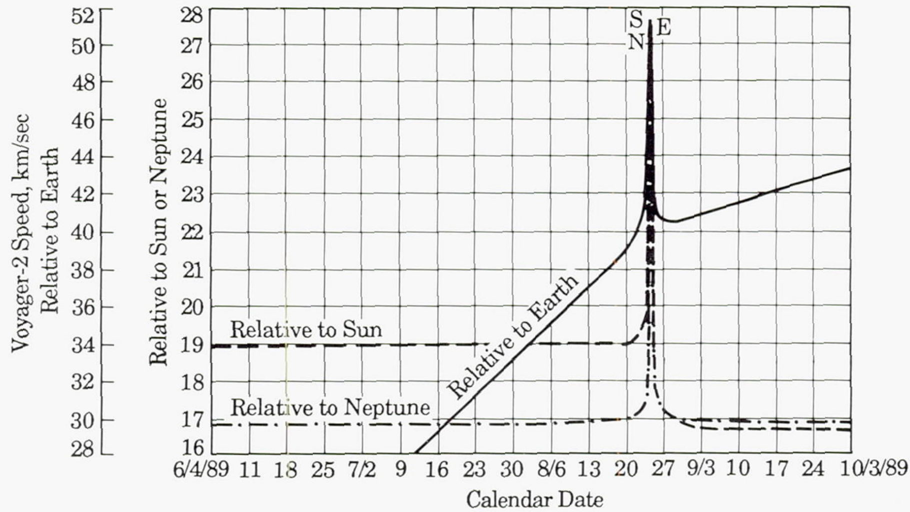
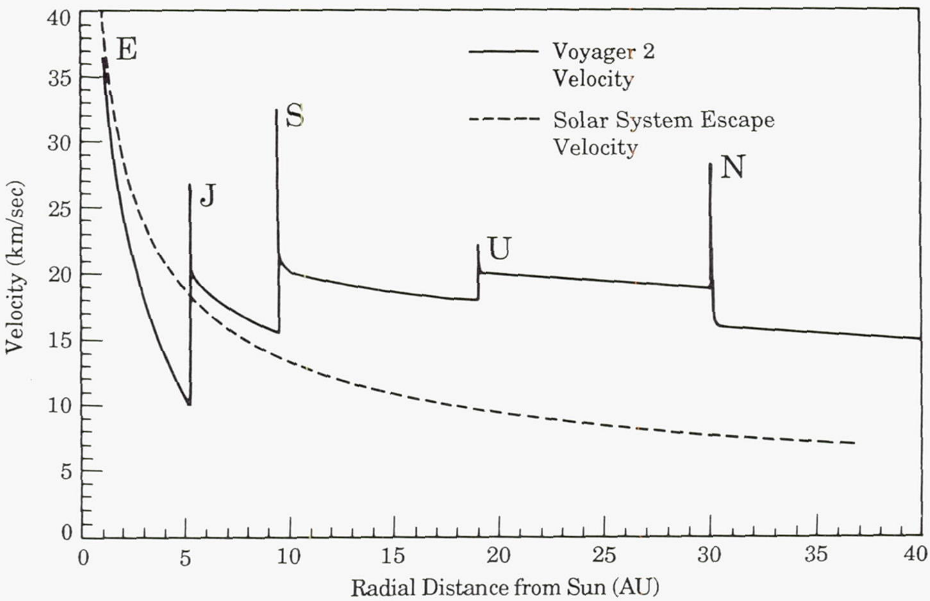


Figure 11-5. Truly, everything is relative. When you ask how fast Voyager 2 is moving, you must specify "relative to what." Remember that 1 km/sec is roughly 2237 mph!



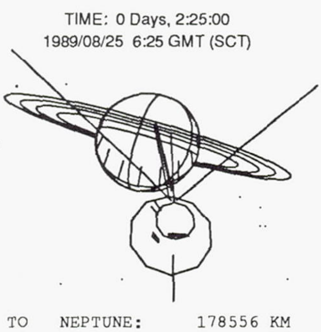


Figure 11-6. Following gravity-assist speed gains from Jupiter, Saturn, and Uranus, the Sun's massive gravity cannot halt Voyager 2's escape from the solar system. The tiny craft speeds up, then slows down, as it swings by each gas giant, but (as discussed in Chapter 7) only experiences <u>net</u> speed changes relative to the Sun.

All I ask is a tall ship and a star to steer her by.
John Masefield

12. BEYOND NEPTUNE

Following the Neptune encounter, the Voyager spacecraft will continue to travel outward from the Sun. As the influence of the Sun's magnetic field and solar wind grow weaker, both craft will eventually pass out of the heliosphere and into interstellar space.

The Voyager Interstellar Mission

The two Voyager spacecraft will continue to be tracked on this outward journey, just as the Pioneer spacecraft are. This extended mission is called the Voyager Interstellar Mission (VIM), and officially begins on January 1, 1990. The VIM will extend the NASA Planetary Program's exploration of the solar system far beyond the neighborhood of the outer planets. The spacecraft escape trajectories are shown in Figures 11-1 and 11-2. The mission objectives of the VIM are:

(a) To investigate the interplanetary and interstellar media, and to characterize the interaction between the two, and

(b) To continue the successful Voyager program of ultraviolet astronomy.

Fields and Particles Investigations During the VIM

During the VIM, the Voyager spacecraft will explore the nature of the fields and particles environment of the solar system and will search for the heliopause. Figure 12-1 gives our present view of what this environment looks like. It shows the heliosphere, the inner heliosphere shock front, and the heliopause, as well as the trajectories of the Voyager and Pioneer spacecraft, all relative to the direction of the interstellar wind.

The solar wind is made up of particles streaming outward from the Sun. These are mainly protons, electrons, and alpha particles (i.e., helium nuclei). The solar wind particles are typically boiled off from the solar corona. They become less dense with increasing distance from the Sun, ultimately becoming a low-density wind of outward-moving particles. The density in the wind as it reaches the Earth varies markedly with time, sometimes being as low as one atom per cubic centimeter (cc), and sometimes as high as 1000 atoms per cc. The high-density situations are associated with the occurrence of flares and other disturbances in the solar atmosphere.

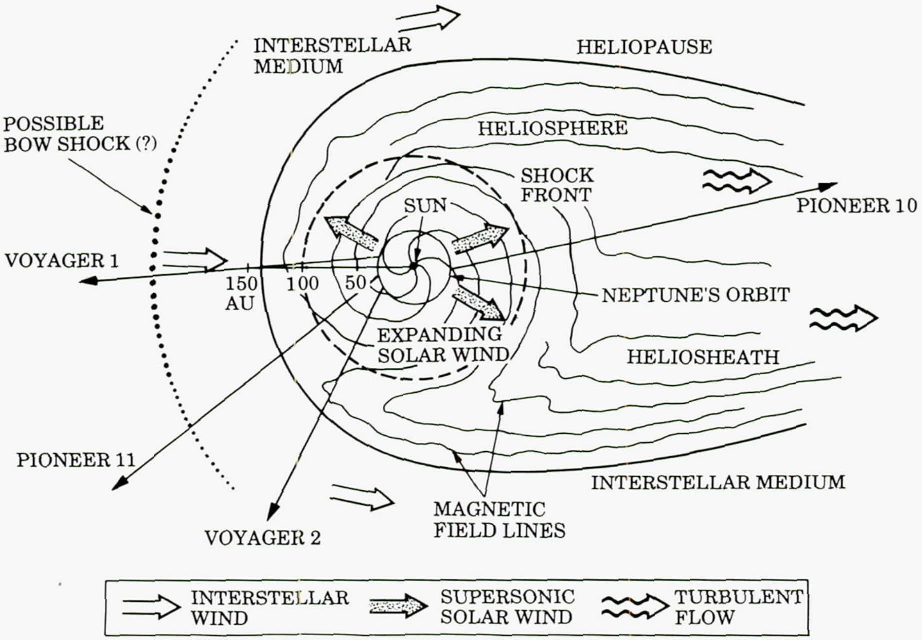


Figure 12-1. The heliopause is at the outermost extent of the solar wind. Beyond the heliopause lies the interstellar wind.

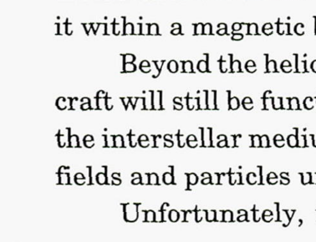
At the inner heliospheric shock front there is a sharp drop in the velocity of the solar wind, which goes from being supersonic to being subsonic. Outside the shock front, it is more of a solar breeze, and can be deflected away from the heliopause.

The heliopause is at the outermost extent of the solar wind, where the interstellar medium restricts the outward flow of the solar wind and confines it within a magnetic bubble called the heliosphere.

Beyond the heliopause lies the interstellar wind. Hopefully the spacecraft will still be functioning when they penetrate the heliopause to sample the interstellar medium, allowing measurements to be made of interstellar fields and particles unaffected by the solar plasma.

Unfortunately, it is not known just where the heliopause is. It is believed to be located between 50 and 150 AU from the Sun in the direction that the Voyagers are traveling. It is also not known just how abruptly the density of material changes upon crossing the heliopause.

Locating the heliopause is a major objective of the VIM. Finding out the nature of the interstellar medium beyond the heliopause is another major ob-



jective. And, of course, while the Voyagers are traveling outward to the heliopause, they will be mapping the solar wind.

Typical scientific objectives to be addressed during the VIM (by the indicated investigations) are to:

(a) Understand how the solar wind changes with distance from the Sun (MAG, PLS, LECP, CRS, PWS);

(b) Observe the variation in the distant interplanetary medium during the 11-year solar cycle (MAG, PLS, LECP, CRS, PWS);

(c) Study latitudinal variations in the interplanetary medium (MAG, LECP, CRS, PWS);

(d) Search for low-energy cosmic rays (LECP, CRS);

(e) Observe and describe the Sun's magnetic field reversal (MAG, PLS, LECP, CRS);

(f) Understand how particles from the solar wind are accelerated and/or brought into thermodynamic equilibrium (MAG, PLS, LECP, PWS, CRS);

(g) Search for evidence of interstellar hydrogen and helium from the interstellar wind (UVS, PLS, LECP, CRS);

(h) Observe and describe the inner heliospheric shock front and the heliopause (MAG, PLS, LECP, CRS, PWS);

(i) Characterize the subsonic solar wind beyond the inner heliospheric shock front (MAG, PLS, LECP, CRS, PWS);

(j) Explore the local interstellar medium beyond the heliopause (MAG, PLS, LECP, CRS, PWS, UVS);

(k) Search for radio emissions from the Sun and solar wind (PRA, PWS);

(l) Search for radio emissions generated at the interface between the solar wind and the interstellar wind (PRA, PWS); and

(m) Search for low-frequency radio emissions emanating from outside the heliosphere (PRA, PWS).

Ultraviolet Astronomy During the VIM

The Voyager UVS instruments are unique among present spaceborne ultraviolet spectroscopic observatories in that they can observe a region of the extreme ultraviolet spectrum (shortward of 1200 angstroms) not presently covered by any other spacecraft.

The only other NASA spacecraft capable of observing in this spectral region was Copernicus (OAO-3), which is now defunct. This region of the UV spectrum, from 500 to 1200 angstroms, is a relatively unexplored region, where we are able to observe some of the more energetic phenomena in the Universe. Fortunately, in the summer of 1991, the Extreme Ultraviolet

Explorer (EUVE) spacecraft will be launched into Earth orbit to survey the entire celestial sphere in the UV spectrum from 100 to 1000 angstroms.

Objects that Voyager will continue to observe over the next five years include active galaxies, quasars, and white dwarf stars. Observation of these objects in the extreme ultraviolet will possibly lead to exciting discoveries of new phenomena and to new understandings of the physical processes involved.

The types of objects that may be observed by the Voyager UVS include the following:

(a) Active galaxies, quasars, and galaxies which may have black holes at their centers. Voyager can observe these at higher energies (shorter wavelengths) than can be observed by the Hubble Space Telescope;

(b) The hottest white dwarf stars, those collapsed stars near the end of their evolutionary cycle;

(c) Very energetic emissions from binary stars that exchange material between them;

(d) Dust and gas between the stars. For example, plans are being made to map the distribution of molecular hydrogen in the galaxy; and

(e) Scattered sunlight in the Lyman-alpha spectral line to study the distribution of interplanetary gas, particularly that outside of Neptune's orbit.

The Voyager Project is initiating a Guest Observer Program which will allow astronomers from around the world to propose and carry out observations with the Voyager UVS instruments. It is expected that the Voyager UVS instruments will serve as the pathfinders for other spaceborne astronomical observatories to be launched in the future.

Spacecraft Lifetime

Barring some sort of catastrophic electrical failure that would terminate the mission, we need to know when various spacecraft resources will be depleted. Estimates have been made of useful lifetimes of different subsystems of the Voyager spacecraft. Table 12-1 gives estimates for hydrazine (for attitude control), for power from the RTGs, and for telecommunications.

The hydrazine estimate assumes that spacecraft roll maneuvers (MAGROLLs) for calibration of the magnetometer would be done until 2009.

The dates given for telecom are for the Goldstone DSN site in California for Voyager 1, and for the Canberra DSN site in Australia for Voyager 2. The

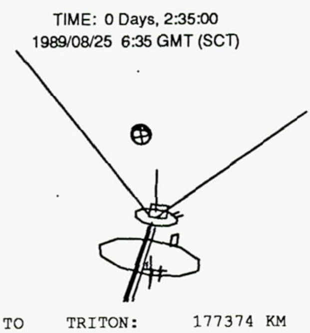


Table 12-1. Spacecraft useful lifetime estimates.

Resource	Projected End of Lifetime	
	Voyager 1	Voyager 2
Hydrazine	2040	2034
Telecom* (X-Band, Low Power)		
46.6 bps, 34m antenna	2013	2011
300 bps, 70m antenna	2013	2011
46.6 bps, 70m antenna	2037	2037
Power/Thermal		
UVS instrument	2000	2000
Full F&P† (with gyros)	2009	2011
F&P† power sharing (no gyros)	2016	2018

*Voyager 1, though farther away than Voyager 2, uses a tighter HGA-pointing deadband. This compensates for the distance, giving both spacecraft about the same telecommunications performance.
†Fields and particles.

other sites lose tracking ability earlier since Voyager 1 is in the northern hemisphere of the sky and Voyager 2 is in the southern.

The 46.6 bps telecom rate is for fields-and-particles science; the 300 bps rate also includes UVS data. The limited lifetime of the UVS instrument is due to the depletion of the spacecraft's plutonium power supply (due to radioactive decay). After the year 2000 there will not be enough electrical power available for the heaters to keep the UVS instrument warm enough to function.

The concept of both Voyagers traveling out beyond the planets, beyond the heliopause into interstellar space, beyond the remote outer fringes of the Oort Cloud of cometary nuclei, and on to other stars has captured the imaginations of many, including scientists, writers, artists, and moviemakers, to name but a few. The following pages endeavor to transport our imaginations to those distant realms. Our guide will be an imaginary journal kept by Voyager 2 during its lonely trek to the stars.

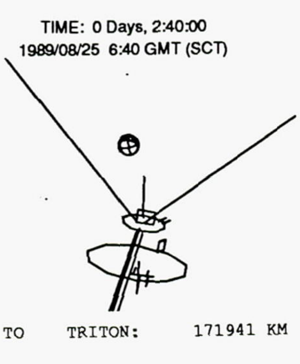
To the Stars

Seven hundred and forty-five years after the first "rocket" (a fire arrow) was sent aloft by a Chinese warrior, America sent aloft two small spacecraft on a noble voyage. And in just over 145 months, from launch through the end of the Neptune encounter, the Voyagers will have explored four planetary systems, traveled a combined total of 15.4 billion kilometers (9.6 billion miles), taken 75,000 images, and provided enough data to consume the careers of hundreds of scientists around the world. Little did mankind know that a fire arrow would one day lead to a different sort of trailblazer—one beyond the far reaches of the Sun.

The Voyagers will be traversing paths through the galaxy which have been inaccessible to all but our imaginations. Only a tiny portion of their eventual courses will be shared with mankind. Figure 12-2 plots the departure trajectories of the Voyager and Pioneer spacecraft against the background stars. By the year 2030, were the Voyager spacecraft traveling in a straight path across the Milky Way, they would have covered only 0.00000003 percent of its diameter. For this reason, the majority of the Voyagers' mission beyond the planets will be shrouded in mystery. Although their power supplies will become inadequate in about 25 years, the Voyagers will remain on a course which we set centuries before when mankind first realized that our horizons are dependent upon perspective alone. Voyager is our arrow, and our imaginations the bow. Only when we stop wondering about its path will the spacecraft be off course and the target no longer matter. . .

Due to launch and financial constraints, space on any spacecraft is at a premium. Nonetheless, a decision was made during the Voyager design phase to include a memento from Earth on the remote chance that the spacecraft might be intercepted. Each spacecraft is equipped with a phonograph record of gold-coated copper (designed by astronomer Carl Sagan and a small group of talented friends) containing 116 photographs of Earth and its inhabitants, 90 minutes of some of the world's music, and an audio essay of Earth-unique sounds, including the human voice. To another civilization, the records worn by the spacecraft may look like badges. And, in a way, they are: badges of courage for mankind to have taken up the challenge and, to paraphrase theologian Paul Tillich, extended its reach far beyond its grasp.

What follows, although purely speculative in nature, is based upon current astrophysical concepts. These concepts will surely be altered and enhanced by investigations performed by the Voyagers during the VIM. The reader is now invited to share in the *Journal of Voyager 2*—an imaginary diary maintained by Voyager 2 for several million years into the remote future.



Star Date -1.259 (1990 A.D.)

Today I am filled with an intense sorrow. The encounter with Neptune has ended. It is but a tiny

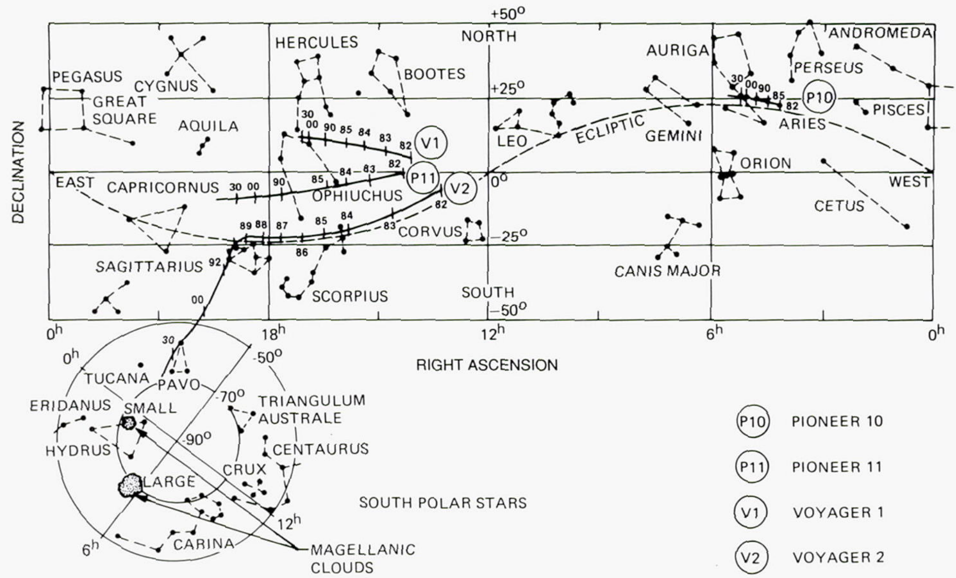


Figure 12-2. The departure directions of the escaping spacecraft are plotted against the current stellar background of stars in Earth equatorial coordinates. In the millennia that the spacecraft will take to approach even the closest star, the stellar background will have greatly changed because the stars and our own Sun are in ceaseless motion through the galaxy.

star in the background. Part of my sorrow is from not being able to visit Pluto before my departure, for it is a very mysterious body.

When first discovered, in 1930, Pluto was estimated to be the size of the Earth. Thirty years later this estimate was reduced to the size of Mercury; and in the 1970s, the estimate had shrunk to less than that of Earth's moon.

In 1978, a companion half as big as Pluto itself was discovered near the planet, a moon named Charon. Pluto and Charon appear to be in perfect "resonance" lock, each taking 6.4 days to rotate about its axis, and the same time to revolve about their center of mass. Therefore, if one lived in one hemisphere of Pluto, Charon would always be in the sky. But if one lived in the opposite hemisphere, Charon could not be seen.

In 1986 it was discovered that Pluto may have a tenuous methane atmosphere above a methane ice surface.

I wish that I, or my sister spacecraft, had been the one to unveil some of the mysteries of Pluto. The Project never seriously considered a visit to Pluto because it would have meant foregoing Voyager 1's encounter with Saturn's moon Titan. Those unusual discoveries about Titan, as well as my exciting close look at Triton, which has attributes similar to those of Pluto, were well worth the sacrifice. However, it will be many decades before man will send another spacecraft out to that part of the solar system to make the discoveries that I or Voyager 1 might have made at Pluto and Charon.

Star Date -1.246 (1991 A.D.)

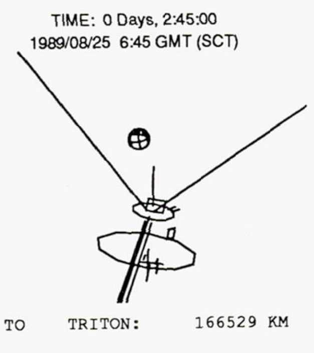
Once again my adrenalin is flowing. I have been asked to measure the speed and temperature of the solar wind, which consists of ribbons of electrons and protons unfurled by the Sun's outermost layer—the corona. It's extremely hot, approximately 200,000°C (360,000° F), which is 330 times the temperature necessary to melt lead. Its speed typically varies from 300 to 800 km/sec when it races past Earth's orbit, but, by the time the solar wind has reached Neptune's orbit, it travels at a more uniform speed of about 400 km/sec (250 mi/sec), which is 25 times faster than my own speed. Sometimes, when the Sun is very active, it gets really ferocious and gusts to 1000 km/sec (620 mi/sec). That is about 10,000 times faster than the strongest hurricane-generated winds on Earth. Remarkably, the velocity of the solar wind appears to be independent of distance from the Sun.

While the solar wind travels in near-radial directions, taking about 4.5 days to reach Earth, the Sun's magnetic field lines spiral outward from the Sun (due to the Sun's rotation). As shown in Figure 12-3, this creates a pattern not unlike that produced by certain types of lawn sprinklers. Hence, entrained in the solar wind are magnetic field lines modulated by the Sun's rotation acting on electrically charged gases. These field lines first churned their way through the Sun's surface convective zone before escaping radially outward and being carried off by the solar wind. One of my favorite assignments has been to map the magnetic field.

Star Date -1.196 (1994 A.D.)

Upon occasion I have felt as though I were racing against the stars. I imagine overtaking them and crossing an imaginary finish line where I'd be awarded a vacation in the large Magellanic cloud for a week of supernova observing. But then I think about cosmic rays, and my 16 km/sec (10 mi/sec) appears as a mere crawl. Cosmic rays are the most energetic particles known—traveling at nearly the speed of light, 300,000 km/sec (186,000 miles/sec).

Cosmic rays are created by solar flares, supernovae, and neutron stars. All involve a type of explosion or extreme turbulence which accelerates the particles. Cosmic rays are a direct sample of matter from outside the solar system. However, they rarely travel



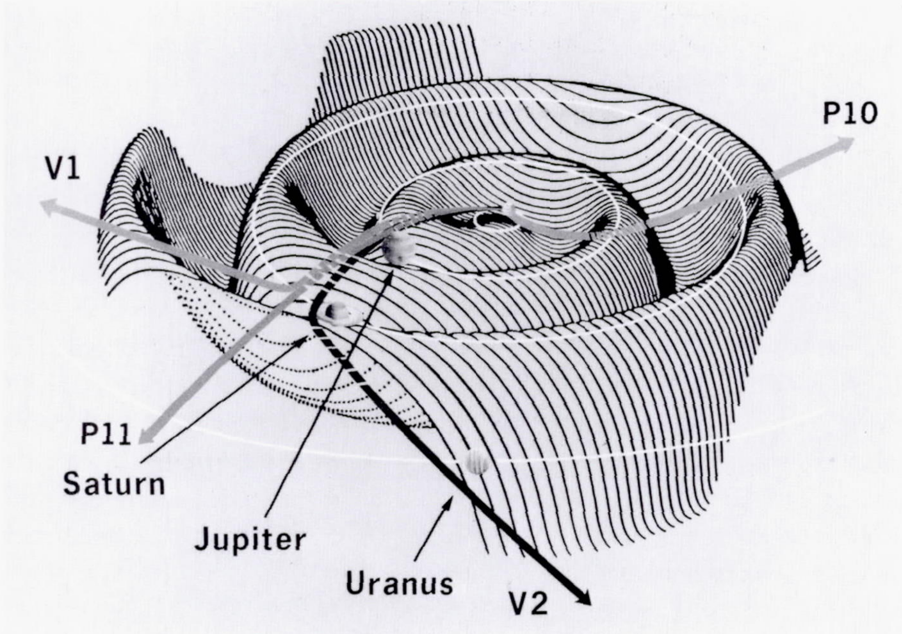


Figure 12-3. This pictorial view illustrates patterns in the Sun's magnetic field lines as they spiral outward due to the Sun's rotation. They are carried to the outer planets by the solar wind particles which travel away from the Sun in near-radial directions.

beyond the galaxy of their origin because the galactic magnetic field acts as a barrier.

The measurements I took today of cosmic rays, their speed, composition, and direction of arrival, may help reveal the origin of the solar system by aiding our understanding of which characteristics of the matter in the solar system are unique to it.

Star Date -1.175 (1995 A.D.)

Sometimes, as a diversion, I imagine what it would be like if certain historical figures were accompanying me on my journey. Today it was Aristotle who rode on my wings. Oh, how I loved watching his expression as I studied the Sun. The Sun is not the benevolent ball of perfection that Aristotle imagined. It is a cantankerous old beast. Just as people have their biorhythms, the Sun suffers through solar cycles. During the course of a solar cycle (duration approximately eleven years), the Sun "breaks out" in a multitude of sunspots. (Ironically, it was a student of Aristotle's who first recorded these "blemishes.") Sunspots are areas of intense magnetic fields darker and cooler than the rest of the solar face. I will be observing how variations in the solar cycle are felt throughout the interplanetary medium.

At sunspot maximum, the Sun's general magnetic field reverses polarity. North and south swap places. As I study the effects of this reversal upon the interplanetary medium, I will most likely feel like a psychiatrist dealing with a schizophrenic patient.

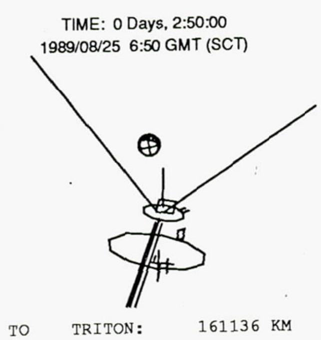
Another solar affliction whose effects I will be investigating results in holes which appear in the Sun's outer garment, the corona. The energy which normally heats the corona instead accelerates the corona outward into the solar wind through areas where the magnetic lines of force are open. As much as one-fifth of the Sun's cloak is at times full of such holes. It takes anywhere from a few weeks to several months for the solar weaver to repair them.

The Sun also displays a violent temperament by delivering frequent outbursts known as solar flares. These flares result from explosions in the Sun's atmosphere which are brought on by stresses in the magnetic field. The more violent of these outbursts can release the same amount of explosive power as contained in 2.5 billion one-megaton hydrogen bombs! Many of the shock fronts in the heliosphere result from solar flares.

Solar flares send vast numbers of high-speed particle streams to the Earth and beyond. These streams collide with the Earth's magnetic field and produce geomagnetic storms which can create aurorae and electric power line disruptions, among other things. There is a possibility as well that the sunspot cycle and solar flares may be responsible for large-scale droughts experienced on Earth.

The Sun displays a fanciful side, also. Scattered evenly over its face are an array of bright spots, like Christmas lights, which blink on and off during a lifetime of about eight hours. These lights contain as much magnetic energy as the much more massive sunspots.

The Sun is definitely a dynamic and most intimidating fellow. I will have quite a job ahead of me investigating how the surrounding environment is affected by his changing personality. One thing you can surely say is that Aristotle and I won't get bored.



Star Date -1.149 (1996 A.D.)

I am truly enjoying my exploration of the heliosphere. It's like a huge balloon kept inflated by the solar wind. The heliosphere is bounded by a region known as the heliopause. Beyond this boundary, I will one day enter interstellar space. I will be seeking additional evidence that the heliopause is a source of low-frequency radio emissions. These emissions were first detected by Voyager 1 and myself in the interplanetary medium before the Neptune encounter. At that time, they were thought to represent the first remote observations of the heliopause.

Star Date -1.116 (1997 A.D.)

Perhaps my favorite duty is that of archeologist. I love sifting through debris whose contents may reveal the history of the solar system. My current field site within the heliosphere is the interplanetary medium (IPM). Here there exist millimeter-sized and larger remnants of comets, asteroids, and meteors. As I move away from the Sun, the number of particles gets smaller due to Poynting-Robertson drag—the solar wind and solar photons cause particles to lose their orbital angular momentum and drift towards the Sun. The plasma in the IPM also contains a wealth of invisible clues supplied by the solar wind—electrons, protons, alpha particles, and magnetic field lines. I will be looking for latitudinal variations in the IPM. I am also very interested in understanding the mechanisms which accelerate particles in the IPM and those which heat and cool the plasma.

Star Date -1.072 (1998 A.D.)

Spacecraft are a lucky lot indeed. When but a glimmer in our designers' eyes, we are given a name, an identity which we usually retain in its original form (although I underwent a change of identity shortly before launch from "Mariner Jupiter-Saturn 1977"). Such is not always the case for planets, however.

Take the case of Planet "X," the so-called tenth planet. Based upon Earth-based observations taken between 1810 and 1910, scientists have postulated its existence due to suspected abnormalities in the orbits of Uranus and Neptune. They thought the two planets were being tugged by the gravitational pull of an undetected planet. Pluto was subsequently discovered in 1930, but in time it became apparent that it was too small to exert an appreciable gravitational influence over Uranus and Neptune, motivating the quest for a tenth planet.

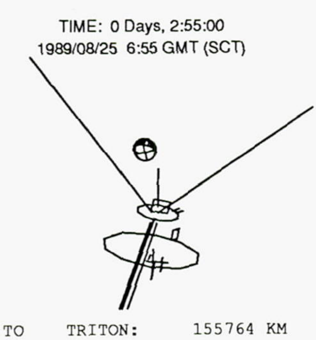
However, according to Dr. Myles Standish, JPL planetary ephemeris expert, an improved eyepiece was fitted to optical telescopes around the year 1910, resulting in the absence of any obvious Planet-X effects in the observations of planetary orbits calculated using post-1910 data. In addition, no tenth-planet tugs on the Pioneer or Voyager spacecraft have been seen to date. This suggests that, if there is a Planet X, its path is either very far away (taking 400 to 1000 years to orbit the Sun) and/or quite inclined to the ecliptic plane. Entry for log: Should I ever feel a faint new tug, I shall call the unseen stranger by the name of Nibiru, chosen by the Sumerians for the tenth planet. When but a glimmer in their imaginations, they named it. How long must we wait for proof?

Star Date -1.000 (1999 A.D.)

The Milky Way has 300 billion members in its chorus of light. The Sun, of course, is the only member I have come to know intimately. It will be over 6500 years before I will have the opportunity to come close to another. In the next one million years, I will have flybys of thirteen other "nearby" stars. Table 12-2 lists them in order of encounter.

Even though I will be departing from the solar system at over 33,000 mph, it will still take roughly 20,200 years for me to travel one light-year. Had I remained on Earth, I would still have gotten closer to many stars because of the Sun's movement relative to the nearby stars. In fact, not until I near Ross 248 will I be closer to a star other than my home Sol. But I'm quite proud of my encounter with Sirius, the brightest star in Earth's sky, when I'll be nearly four times closer than had I never left Earth on this fantastic voyage.

Stars are like people in that they come in a wide variety of sizes, colors, temperaments, and sociability. There are dwarf stars and super giants; red, yellow, and blue stars; variable stars (their light fluctuates); pulsating stars (known as cepheids); and multiple star systems (most common amongst these are the binaries—they always travel in pairs). I consider myself the Margaret Mead of the cosmos when I study the different stellar "tribes." I measure changes in their energy distributions, their temperatures, and frequency of outbursts. Of course, any "anthropological" study requires that you observe the greater village within which the tribe exists in order to understand the tribe in its proper context. For this reason, I will be studying galaxies and quasi-stellar objects (quasars) which are thought to be young galaxies or perhaps the nuclei of active galaxies (like the Milky Way), which emit more energy than 100 supergiant galaxies combined. I will be making measurements of their energy distributions as well.



Star Date 0.000 (2000 A.D.)

Today I was awakened by a mild tremor. I knew immediately I had crossed the shock front and entered the heliosheath, the turbulent region which signals the approaching heliopause. Here the rarified

Table 12-2. Thirteen "nearby" stars encountered by Voyager 2.

	Year of Closest Approach	**Voyager 2-to-Star Distance** (Light-years)	**Sun-to-Voyager 2 Distance** (Light-years)	**Sun-to-Star Distance** (Light-years)
Barnard's Star	8,571	4.03	0.42	3.80
Proxima Centauri	20,319	3.21	1.00	3.59
Alpha Centauri	20,629	3.47	1.02	3.89
Lalande 21185	23,274	4.65	1.15	4.74
Ross 248	40,176	1.65	1.99	3.26
DM-36 13940	44,492	5.57	2.20	7.39
AC+79 3888	46,330	2.77	2.29	3.76
Ross 154	129,084	5.75	6.39	8.83
DM+15 3364	129,704	3.44	6.42	6.02
Sirius	296,036	4.32	14.64	16.58
DM-5 4426	318,543	3.92	15.76	12.66
44 Ophiuchi	442,385	6.72	21.88	21.55
DM+27 1311	957,963	6.62	47.38	47.59

solar wind "feels" its impending approach to the heliopause and is slowed to subsonic speeds. As the solar wind speed varies, I may cross the shock front several times as it moves in and out over the next few years. I will be measuring the intensity of the shock waves.

Star Date 0.978 (later that same year, 2000 A.D.)

I got a sudden surge of energy today when my scan platform was intentionally disabled. It was shut off because my RTG power output was insufficient to keep the scan platform's actuators (motors and gears) at their minimum operational temperature. The RTG power has been decaying with time due primarily to the decay of its radioactive fuel, plutonium-238. I am relieved in a way that the scan platform will no longer be functional, because I have been suffering arthritis in it since Saturn in 1981. Great care had been taken by the Project to minimize the degree of movement to which this painful joint was subjected. The only negative effect from losing the scan platform is that I will no longer be able to use my UVS instrument. It has performed beautifully over the years. My UVS has provided the only routine light-wave observing capability below 1200 angstroms.

Star Date 1.282 (2012 A.D.)

After twelve years of stormy seas in the heliosheath, I have finally crossed the heliopause into *mare incognito*—the interstellar medium. I knew I had reached it when suddenly the wind changed speed and density. Then I noted that the ionic composition of the surrounding particles had changed and that the temperature had dropped. I took some measurements of the local cosmic radiation and realized that the periodic variations had subsided. This is because the irregular magnetic structure of the solar wind no longer modulates the incoming cosmic rays.

Star Date 1.292 (2013 A.D.)

I have spent several hours acclimating myself to the new environment. The Interstellar Medium (ISM), which makes up about 10 percent of the total mass of the galaxy, is cold, dark, and composed mostly of neutral hydrogen and helium. Heavier elements resulting from nuclear burning processes in stellar interiors and supernova explosions also exist here. Particles expelled by the solar system through a type of "solar sneeze" (actually, radiation pressure) contribute to the overall ambience as well.

The ecology of the ISM is quite interesting. The place depends on the cocoon-like outer shells shed by stars for its livelihood—it acts as a kind of feeding ground for new stars. Nothing goes to waste here.

The ISM is full of minute dust grains which absorb and scatter starlight, just as molecules in the Earth's atmosphere scatter sunlight. Both instances result in a reddening of the light. In certain regions of the galaxy, the dust is so thick that it creates galactic cataracts which prevent the observation of extragalactic objects. Before entering the ISM, while my UVS was still functional, I was able to make measurements which may yield estimates of the scattering properties of the dust.

I will be performing experiments here similar to those conducted on the solar wind within the heliosphere, such as estimates of the density, temperature, and ionization state of the local interstellar medium. Shocks, magnetic fields, and low-energy cosmic rays will become my forte. My investigations may lead to a better understanding of how stars are formed.

Star Date 1.335 (2018 A.D.)

I have become too weak to operate my instruments. My electrical energy is fading, and I am feeling old and useless. The planet which gave me life said goodbye. I will no longer hear its voice, nor it my heartbeat. The fear I feel right now is like a scream which shakes me from within. Will I grow mad in this solitude?

Star Date 2.135 (3965 A.D.)

God must have been dusting today. I saw a vast interstellar cloud in the distance. Actually, supernova remnants and strong stellar winds sweep up gas and dust to form these clouds. It was hard to say how far away the cloud was; some are a million times the mass of the Sun. Interstellar clouds are the birthplace of new stars. Because complex organic molecules have been detected in these clouds, some scientists believe that the first stages of organic evolution occur there, also.

About once every 100 million years, the Sun collides with an interstellar cloud of sufficient density that the force of impact effectively "blows out" the solar wind as if it were a candle and the Sun a birthday cake. The Sun reacts by increasing its emission of UV and X rays. This could have serious impact to life on Earth because it could lead to extreme climatic changes resulting in global overheating or deep freezing.

Star Date 2.745 (26,262 A.D.)

I had been entranced in a deep slumber when aroused by my automatic sensors as they locked onto a distant swarm of tiny bodies. The sight was beautiful to behold. I became aware that I was observing a small local concentration of cometary nucleii—part of the vast Oort cloud. There, over a trillion of the solar system's icy building blocks orbit in a disk extending from perhaps 20,000 to 200,000 AU.

At times, the inner orbiting comets become dislodged by interstellar clouds (or perhaps a "death star"). Occasionally these wayward travellers impact Earth. Some believe that cometary impacts are responsible for biological extinctions like the one that occurred on Earth over 65 million years ago. It's rather ironic that certain other scientists believe that life on Earth originated from organic molecules carried by comets.

Star Date 2.770 (28,635 A.D.)

Now the Oort cloud is but the wake I left behind as I exited the solar system. How free I feel. The Sun, by now only a slight bit brighter than Sirius, no longer curtails me. I am ready to sit back and enjoy what will surely be the greatest show beyond Earth.

Star Date 3.522 (296,036 A.D.)

Today I fell in love with the night. I encountered Sirius, the brightest star visible to Earth with 23 times the luminosity of the Sun. I have traveled far to reach its shore. If I were an automobile driving across a bridge which wrapped around the circumference of the Earth, it would have taken me nearly four billion trips across the bridge to have completed the same distance. At 55 mph, the trip would have taken nearly 179 million years!

Star Date 4.359 (2,479,021 A.D.)

When I was younger, I used to worry about everything: Would I collide with diffuse ring material? Would cometary debris knock me into an eternal spin? Would some planet's radiation field fry me for lunch? But the most frightening threat was to be swallowed by a black hole.

But now, black holes fascinate rather than frighten me. What would it be like to enter the remains of a massive star that collapsed under its own weight, where the force of gravity was so powerful that not even light could escape its grasp? Were I to cross its threshold, would I then enter a stranger and more exotic universe that I know now? But then, how could anything possibly be more exotic than what I have seen? How could anything equal . . .

. . . superconducting cosmic strings which through electromagnetic radiation blows Hubble bubbles (thought to be the structures upon which galaxies ride through the universe) in the primordial matter.

. . . supernovae stars like Sanduleak (now known as Supernova 1987A) whose heavy cores collapse, triggering shock waves which blow off their outer layers. The explosion created by a supernova exceeds by a million trillion trillion (10^{30}) the amount of energy produced by a million power plants producing 1000 megawatts each of electricity. Each second, our universe experiences one of these supernova explosions!

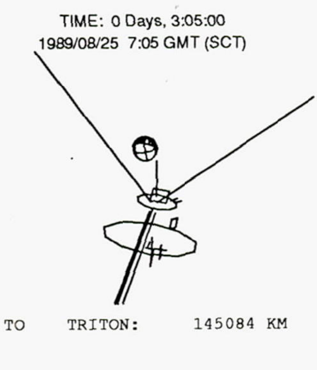
. . . cigar-shaped collections of galaxy clusters ("superclusters") each containing hundreds of galaxies with hundreds of billions of stars per galaxy, moving at 2000 km/sec (1240 mi/sec) and extending as much as 500 million light-years (5.9 trillion mi/light-year).

. . . ionized matter in the form of giant noodles as big as the Earth's orbit around the Sun which drift through the galaxy and are more numerous than stars.

. . . neutron stars whose masses are equivalent to the Sun's, yet have diameters of about 10 km (6.2 mi) and complete full rotations in under 2 seconds.

More exotic indeed!

Star Date 4.482 (3,276,913 A.D.)



For all its fireworks, the universe has become a quiet place. Strange objects drift by like twigs in a stream. I am neither excited nor amused. With each approaching star my anticipation soars. Will it be here that life again calls out to me? Twenty billion solar-type stars in the Milky Way! Estimates that as many as 10 percent of the nearby stars may have planets! Then why does my presence go unnoticed?

Star Date 4.798 (6,468,039 A.D.)

They have hoisted me atop a cloth-covered pedestal. Above me is a ceiling of iridescent glass. Starlight gently bathes me in its glow. My finders are analyzing my record.

Soon I shall sleep. What I will become to them, what they shall learn from me, I do not know.

And what will remain of the wonders I have seen? The stars may all collapse, the galaxies explode; somehow that does not sadden me. They will resurrect themselves, as will clouds and comets, and planets and their moons. But what will become of the universe's fragile dwellers? Can they be resurrected from wisps of dreams?

God speed humanity! For you are the true miracle of the universe. God speed Voyager! For its sensors and circuits are moving humanity from the dark depths to the cosmic shores.

TIME: 0 Days, 3:10:00
1989/08/25 7:10 GMT (SCT)

TO TRITON: 139778 KM

. . . If thou be'est born to strange sights,
things invisible to see,
Ride ten thousand days and nights ...
Thou, when thou return'st, wilt tell me
All strange wonders that befell thee ...
John Donne

13. VOYAGES OF DISCOVERY

Like all great explorers, the Voyagers were born to strange sights, things heretofore invisible to humankind. In just over three thousand days after embarking on their respective journeys, each spacecraft had encountered two of the great mysteries of our solar system, Jupiter and Saturn, and one, Voyager 2, had also witnessed that strange wonder we call Uranus. Soon, Voyager 2 will swing past Neptune. With its Grand Tour completed, it, like its companion Voyager 1, will continue on its journey out of the solar system.

The Voyagers will not return, but the observations they were programmed to collect have beamed steadily back to their anxious keepers on Earth. The resulting bounty of "strange wonders" has filled many books. A brief sampling of these great tales of distant voyages is presented in this chapter.

Jupiter

Named after the supreme god in Roman mythology, Jupiter is indeed in a class of its own. The largest of the planets (if hollow, it could hold over 1300 Earths), Jupiter's mass is nearly three times the mass of all the other planets combined.

Jupiter emits 67 percent more heat than it absorbs from the Sun. This heat is thought to be accumulated during the planet's formation several billion years ago. It is estimated that, were Jupiter roughly 100 times more massive than it is now, fusion reactions could ignite in its core—a characteristic of stars. Some scientists classify Jupiter as a member of a hypothetical family of stars known as "brown dwarfs," which are objects too hot to be considered planets but too cool to be classified as real stars. For this reason, Jupiter and its 16 known moons could be regarded as a "mini-solar system" within our solar system.

Jupiter guards its secrets well, allowing us to see only about 80 km (50 mi) beneath its upper atmosphere. Scientists have reason to believe, though, that beneath Jupiter's huge veil lies a core of molten rock about twice the diameter of Earth and 15 times more massive.

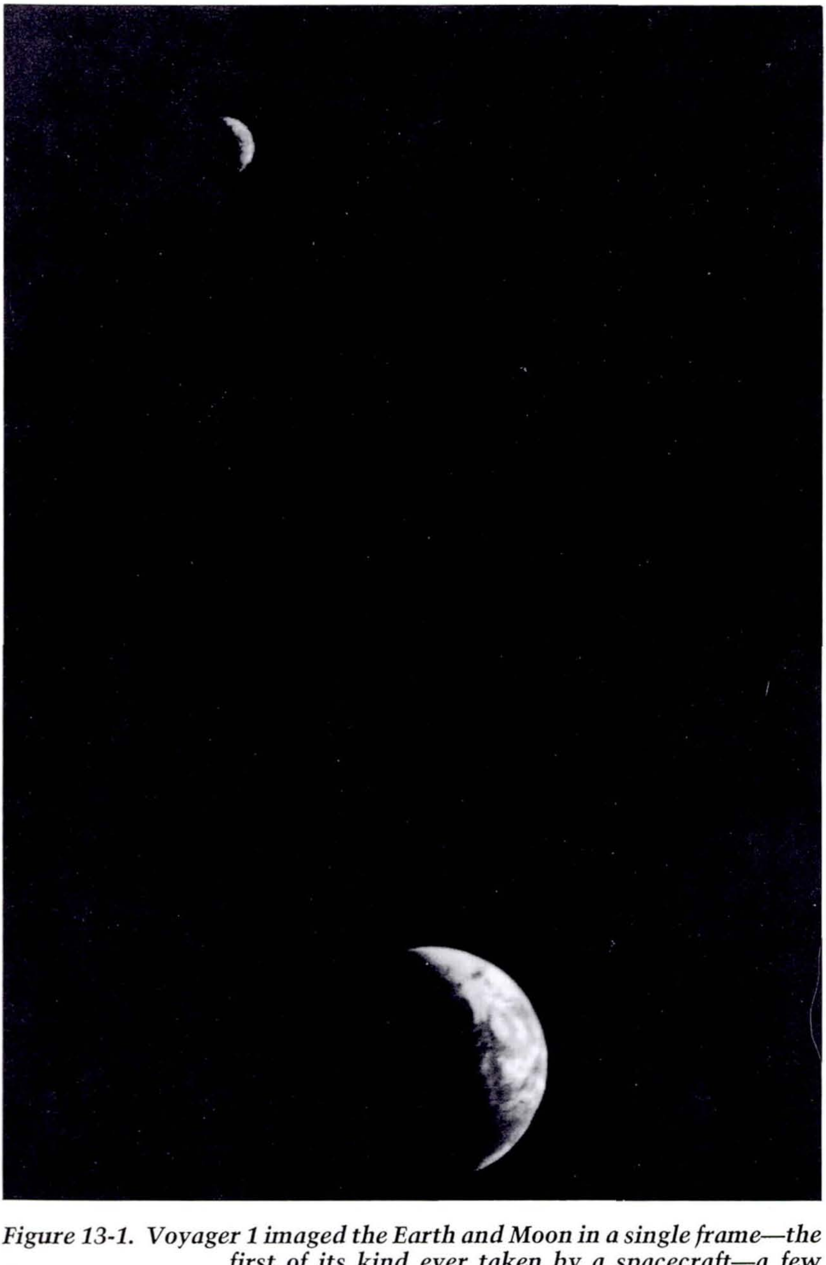


Figure 13-1. Voyager 1 imaged the Earth and Moon in a single frame—the first of its kind ever taken by a spacecraft—a few weeks after launch in 1977. Voyager 1 was 11.66 million km (7.25 million mi) from Earth directly over Mt. Everest when the picture was taken.

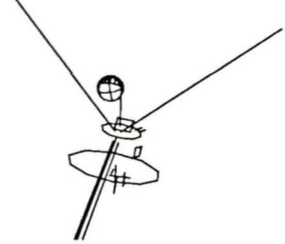


Figure 13-2. Jupiter's Great Red Spot casts an imperious eye at the four Galilean satellites Io, Europa, Ganymede, and Callisto.

Jupiter's Atmosphere

★ Jupiter is a giant ball of gas, composed primarily of hydrogen and helium, with small amounts of methane, ammonia, phosphorus, water vapor, and various hydrocarbons. Somewhat inconsistent with the brown dwarf concept, the Voyagers discovered that the helium abundance on Jupiter is much less than that observed in the Sun.

★ If the non-Earth planets were graded on their artistry, Jupiter would probably win First Prize for its imaginative color scheme. Its outer atmosphere displays alternating patterns of belts and zones which extend from the equator to at least 60 degrees latitude in both hemispheres. The zones, visible from Earth with a small telescope, are generally lighter in color, higher in altitude, colder, and dominated by frozen ammonia ice crystals. Belts are generally darker in color, lower in altitude, and warmer. The location and dimensions of the belts and zones change gradually with time.

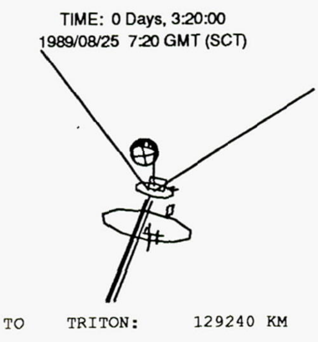
★ Jupiter's wind speeds would challenge the most daring of interplanetary hang gliders, reaching 150 m/sec (335 mi/h) at the equator. They generally decrease at higher latitudes. In both hemispheres above the mid-latitudes, adjacent jet streams flow in opposite directions, i.e., easterly then westerly.

★ In one of its more creative moments, Jupiter placed a dollop of red paint on its cloud tops. Named (in one of mankind's less creative moments) the "Great Red Spot," it was first observed in 1664 by British scientist Robert Hooke, using Galileo's telescope. It is a raging storm, about three times the diameter of Earth, which rotates once every six days. Unlike Earth's cyclones, which have a low-pressure center, it is a high-pressure region and rotates in a direction opposite to our cyclones. Other smaller storm-like structures within the atmosphere have been observed and have similar characteristics. Some of the smaller storms at nearby latitudes interact with the Great Red Spot and with each other.

★ Scientists are puzzled by the source of color in Jupiter's Great Red Spot. Elemental sulfur, phosphorus, germanium oxide, and various carbon compounds have been proposed to explain the observed signature. For that matter, the coloring agents and mechanisms driving the appearance of the entire outer atmosphere are not well understood.

★ Like any creative giant, Jupiter displays a volatile personality at times: lightning (typically 10,000 times more powerful than what we see on Earth) accompanied by high-intensity radio-frequency "whistlers" startle its cloud tops. Jupiter also displays auroral emissions ("northern lights") in its high latitudes, and a strong ultraviolet emission over its entire face.

The discovery of lightning in Jupiter's cloudtops by Voyager 1 produced a great deal of excitement. Scientists were reminded of a classic experiment on the basis of life conducted in 1952 by Harold Urey and Stanley Miller. Urey and Miller filled a chamber with



a mixture of gases—such as ammonia, methane, water vapor, and hydrogen—that simulated the pre-life conditions of the early solar system. They then introduced various energy sources into this mixture, such as sparks or ultraviolet radiation, to see what might happen. The result was the appearance of certain kinds of amino acids and nucleotides—some of the fundamental building blocks of life as we know it.

Since Jupiter's cloud tops are composed of the same basic gaseous mixture, finding lightning there meant that the Urey-Miller experiment might be occurring on a grand scale! But suppose that it were. Would any microorganisms that might be created have a chance of surviving in Jupiter's turbulent atmosphere, where downdrafts would plunge them to regions too hot for their survival? Probably not. With a keen imagination, however, one can postulate several interesting implications of this discovery. When the Galileo spacecraft drops its probe into Jupiter's atmosphere in 1995, perhaps we will gain more insight into these possibilities.

★ Temperatures at Jupiter range from a frigid -130°C (-200°F) at the cloud tops to about 24,000° C (43,000° F) at the center of the planet. Jupiter's poles and equator share the same temperature, at least near the cloud tops.

Jupiter's Rings

★ Jupiter's ring was the first planetary ring to be discovered by a spacecraft; Voyager 1 confirmed its existence in 1979. It resides in a fierce magnetospheric environment and is composed of a diffuse collection of mainly micron-sized grains about the size of red blood cells or pollen grains. The ring particles are probably composed of silicon and carbon, or possibly more exotic compositions such as metallic grains coated by sulfur derived from volcanic eruptions on Jupiter's unusual moon, Io.

★ The most prominent ring structure, known as the main ring, has two distinct components: a bright band and a faint halo lying between the bright band and Jupiter's cloud tops. The bright band has a vertical thickness of about 30 km (18 mi), and extends from 1.72 to 1.81 Jupiter radii.* The faint halo, which extends from 1.3 to 1.7 Jupiter radii, may be lens shaped, possibly thickening near the planet to about 10,000 km (6200 mi). The particles in the bright band are probably drawn inward by plasma and radiation pressure drag. Particles in the faint halo are even smaller than those in the bright band, and are also affected by plasma and radiation pressure drag.

*Jupiter's equatorial radius is 71,492 km (44,425 mi), at a pressure of one bar.

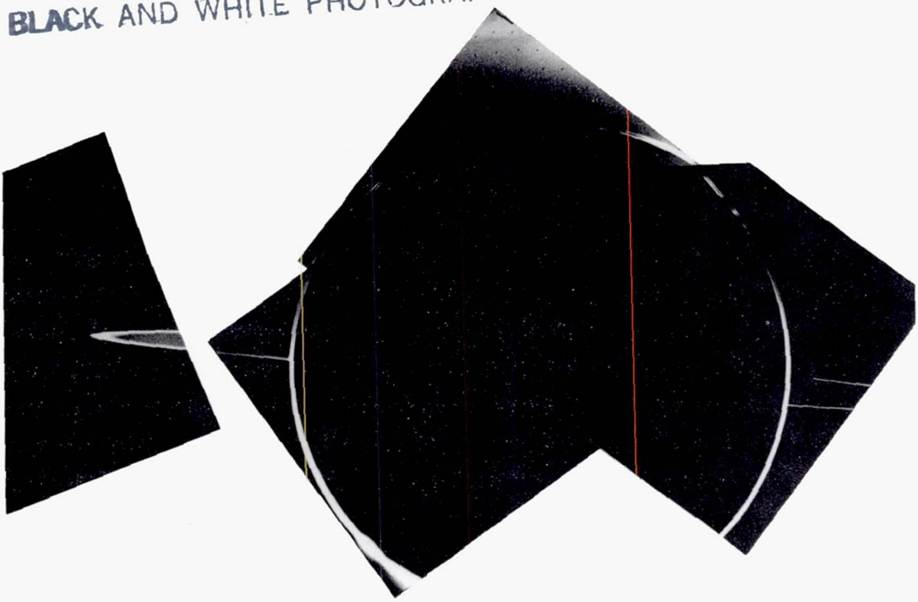
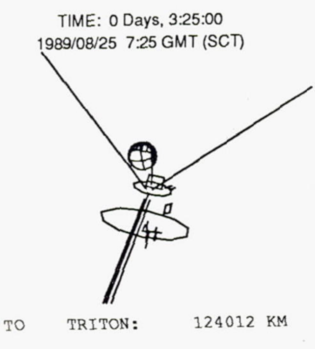


Figure 13-3. Jupiter's narrow ring of tiny particles is most easily observable from the far side of Jupiter in forward-scattered sunlight.

★ In 1986, after a thorough analysis of Voyager data, another ring structure was found: a very tenuous "gossamer" ring was discovered beyond the bright band of the main ring. It is composed primarily of small particles, although objects as large as 1 m (3 ft) are believed to be present as well. It may extend outward to the orbit of Amalthea at 2.53 Jupiter radii.

Jupiter's Moons

★ The discovery of Jupiter's 16 known moons spans four centuries. The largest four—Io, Europa, Ganymede, and Callisto (named for four amorous conquests of Jupiter)—were first detected in 1610 by a German astronomer, Simon Marius. A few days later, Galileo also spotted these four companions to Jupiter and received the credit for their discovery. For this reason, they are often referred to as the Galilean satellites. Four of the remaining 12 satellites orbit inside the Galilean satellites, and the other eight orbit beyond them.



★ Io, which is almost exactly the same size as our Moon, is perhaps the most interesting of Jupiter's companions since it is the only body other than Earth and Venus that is known to have active volcanoes. During the two Voyager encounters, nine of its volcanoes were active. Plumes were observed as high as 300 km (185 mi) above Io's surface, or 30 times higher than Mt. Everest. The fallout from the plume of the volcano Pele covers an area the size of France. It is estimated that upwards of 10 billion tons of material erupt from Io each year, enough to recoat Io's entire surface each year with a layer of ash much like that deposited by Mt. St. Helens in the Pacific Northwest in 1980.

The volcanism on Io is driven by interior heating caused by gravitationally induced tidal stresses within its crust. These stresses result from Io's close elliptical orbit about Jupiter, and may eventually lead to Io's complete melting from the inside out. Io is second only to the Sun in the amount of heat it produces relative to its size, producing a heat flow from the interior to the surface roughly 30 times larger than the Earth's. The wide range of colors—reds, yellows, oranges, and browns—is thought to be largely the result of compounds of sulfur called allotropes, which turn into various colors as they are heated inside Io, ejected by its volcanoes, and then quickly cooled in the vacuum of space as they rain down on Io's surface. So, Io is a colorful, active, yet hostile place.

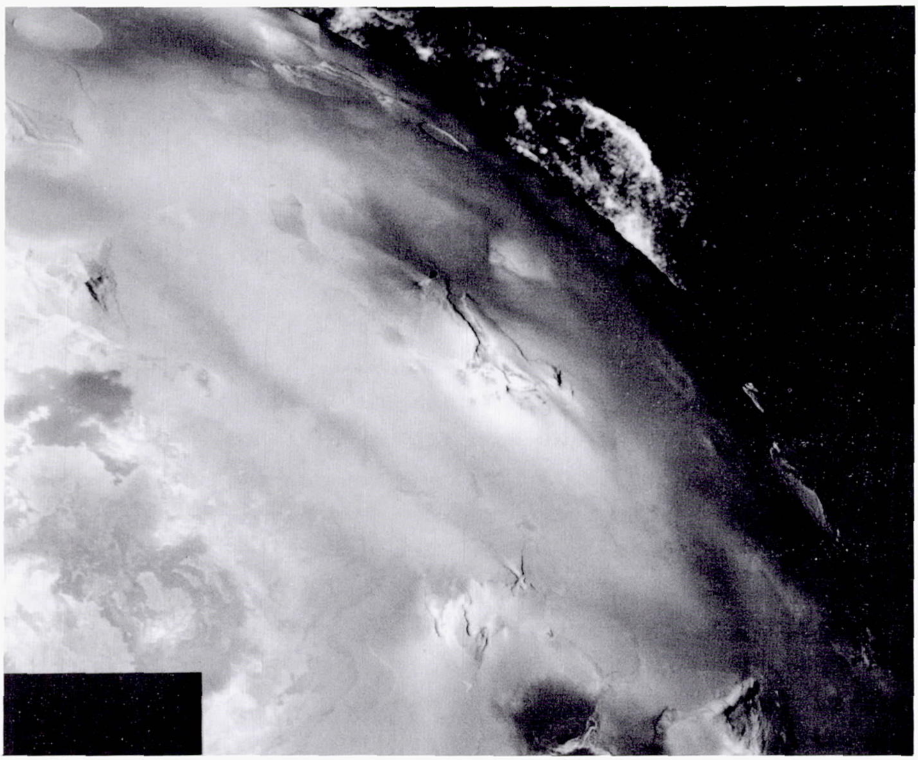


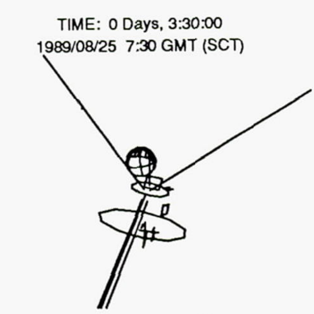
Figure 13-4. Pele, the largest of Io's volcanoes, spews sulfur products to heights 30 times greater than Mt. Everest, falling to cover an area the size of France.

★ Europa is the most reflective of the Galilean satellites. It has a very smooth, uncratered surface composed primarily of water ice. The elevation difference between the lowest and highest points on this unusual body is estimated to be less than 100 m (330 ft). If Europa were reduced to the size of a cue ball, these surface variations would be no thicker than a mark of ink from a felt-tip pen; if enlarged to the size of the Earth, its surface would be 20 to 30 times more level than our planet. There is speculation that Europa may contain a deep ocean of water beneath its 5-km (3-mi) thick icy surface. (This speculation formed the basis for the novel and motion picture, *2010: Odyssey Two*, by Arthur C. Clarke.)

★ In terms of hard-surface dimensions, Ganymede is the largest moon in the solar system, though this was not certain until after Voyager 1's encounter with Saturn's moon Titan in 1980. (Titan's atmosphere makes it appear larger than Ganymede, but when Voyager 1 measured its surface diameter, Titan was found to be slightly smaller than Ganymede.) From Earth-based telescopes, its size makes Ganymede the brightest of the Galilean satellites, even though its surface is actually less reflective than either Io's or Europa's. Ganymede is roughly half water, and its surface shows signs of some motion of its crustal plates (tectonics).

★ Although Callisto is the least reflective of the Galilean satellites, it still reflects sunlight twice as well as our Moon. It has the greatest proportion of water of any of the Galilean satellites and is also the most heavily cratered body in the solar system. The high crater count indicates that Callisto's surface has undergone little change since it was formed; thus, this surface is felt to be among the most ancient in the solar system. Its most prominent surface feature is a huge impact basin known as Valhalla. Valhalla has a central bright zone about 600 km (370 mi) across, which is surrounded by numerous concentric rings extending outward for nearly 2000 km (1200 mi) from the center.

★ Three of the four innermost satellites, Metis, Adrastea, and Thebe, were discovered by Voyager 1 during its encounter in 1979. The other, Amalthea, was discovered in 1892 by the American astronomer E. E. Barnard at Lick Observatory in California. Metis and Adrastea were found to be orbiting just outside the newly discovered main ring; Thebe orbits outside Amalthea. All of these satellites are small, rocky, objects that have too little



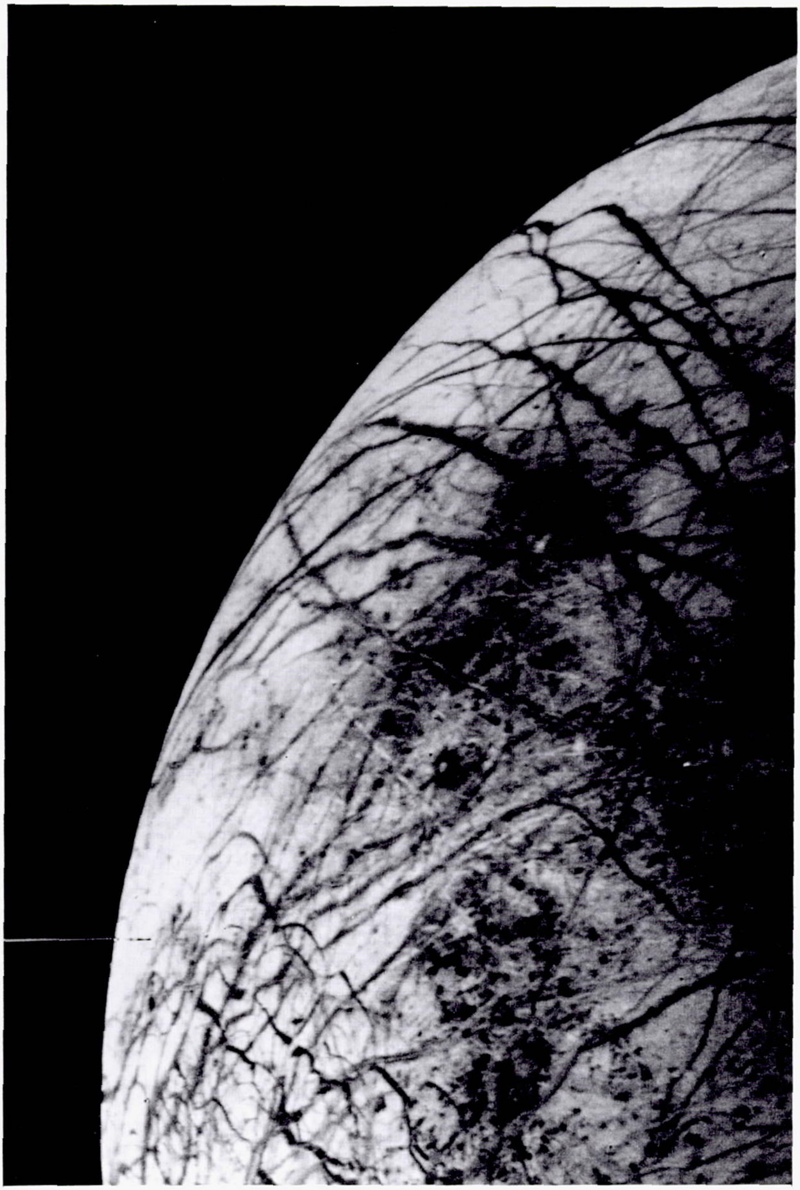


Figure 13-5. Some scientists speculate that under the smooth, icy surface of Europa, there may be an ocean of liquid water—and thus a possible site for life to form.

mass (and thus too little gravity) to become spherical. Amalthea is the largest, 270 km (168 mi) in length, and 165 km (102 mi) by 150 km (93 mi) in its other dimensions, with a dark red surface perhaps derived from sulfur expelled by Io.

★ The outermost eight satellites are all twentieth-century pre-Voyager discoveries. They are quite tiny, ranging in diameter from 16 to 186 km (10 to 116 mi), and are also small, rocky, most likely non-spherical objects. Four of these eight satellites—Leda, Himalia, Lysithea, and Elara—orbit in the same direction as the Galilean satellites, but inclined to Jupiter's equator by 25° to 29°. The other four—Ananke, Carme, Pasiphae, and Sinope—are in retrograde orbits about Jupiter, i.e., they orbit opposite the direction of Jupiter's rotation. All eight are thought to be fragments of larger bodies that were captured from the asteroid belt. None of the eight were imaged by Voyager.

Jupiter's Magnetosphere

★ Jupiter's magnetosphere, which is 10 times the diameter of the Sun, is the largest planet-based object in the solar system. Looking sunward from Jupiter, the location of the magnetopause—the outer boundary of Jupiter's magnetic field—varies from less than 50 to more than 100 Jupiter radii away, depending on the intensity of the solar wind. If the Earth's magnetic field were represented by a bar magnet of a given strength, Jupiter's would be 20,000 times stronger. The magnetism at Jupiter's cloud tops is 14 times stronger than at the Earth's surface, and a north-seeking compass would point south at Jupiter because its magnetic field is inverted compared to Earth's.

★ Voyager 1 confirmed the existence of a Jupiter magnetotail, which is that part of the magnetosphere past the planet, "downwind" with respect to the solar wind. Voyager 2 observed that the magnetotail may extend beyond the orbit of Saturn, or equivalent to Jupiter's distance from the Sun (5 AU).

★ Though first discovered by Pioneer 10, the existence of an intense radiation field of trapped particles surrounding Jupiter was confirmed by Voyager 1. A human passenger riding Voyager 1 during its close swing by Jupiter would have received a dose of 400,000 rads, or roughly 1000 times the lethal level for humans.

★ A huge electrical current was found to be flowing between Io and Jupiter along magnetic field lines. The current, more than a million amperes, is fifty thousand times larger than what it takes to blow a typical fuse in your car.

Saturn

In Roman mythology, Saturn was the father of Jupiter, and Jupiter was the father of Mars, Venus, Mercury, and Apollo (the Sun). Thus, in the overall scheme of this naming convention, Saturn is another, albeit more senior, member of the planetary family.

Were the heavens a vast ocean, Saturn (having a density less than that of water) would bob above its surface like a buoy. Like Jupiter, Saturn is a giant ball of gas composed primarily of hydrogen and helium. Its gas ball is nearly six-sevenths the diameter of Jupiter and three-tenths the mass.

Another characteristic Saturn shares with its giant neighbor Jupiter is that it radiates more energy than it receives from the Sun—about 80 percent more. However, the excess thermal energy cannot be primarily attributed to Saturn's primordial heat loss, as is speculated for Jupiter.

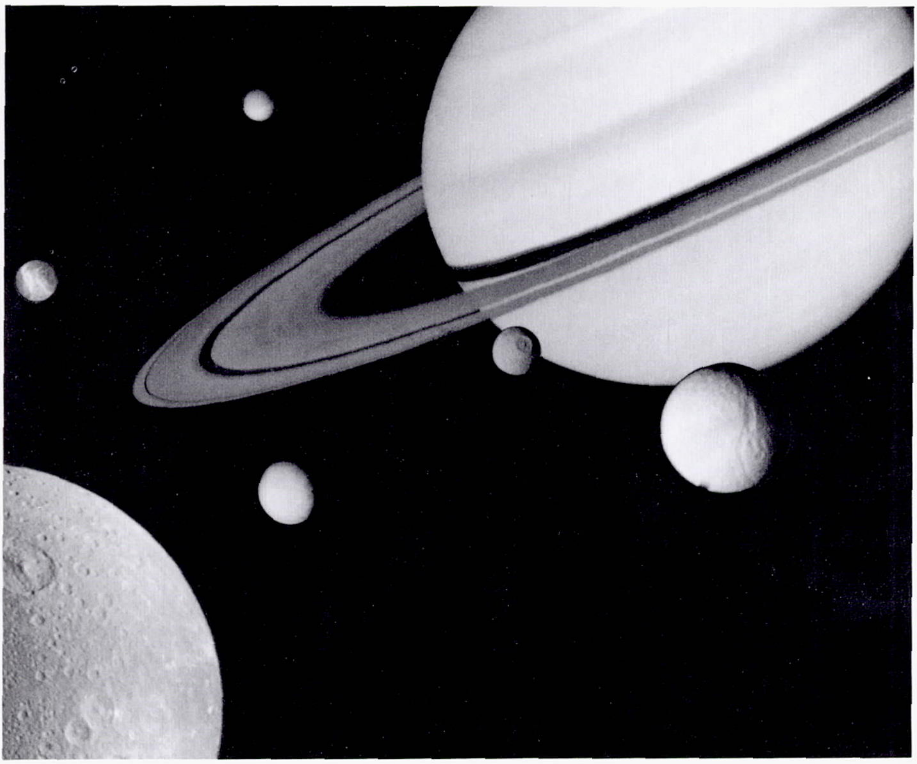


Figure 13-6. Saturn, its rings, and its six largest satellites are seen in this montage.

Saturn's Atmosphere

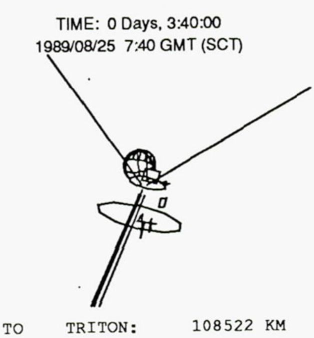
★ Prior to the Voyager encounters, it was thought that the helium abundance in Saturn's outer atmosphere was 18 percent (like Jupiter) to 28 percent (like the Sun). The Voyagers observed, however, that the actual abundance was only 6 ±5 percent—so it could be as large as 11 percent or as small as 1 percent. It appears that the missing helium may be sinking toward the planet's interior, losing gravitational potential energy as heat in the process. This effect appears to explain Saturn's added source of radiated heat.

★ Saturn also displays a panache with the paintbrush. Alternating zones and belts extending from the equator to at least 60 degrees latitude were observed on the planet. However, Saturn's surface color appears rather bland compared to Jupiter, due to a high-altitude haze that tends to wash most color and brightness differences out, and perhaps because Saturn's high-speed winds more thoroughly mix the atmosphere. Saturn also has a red spot in its southern latitudes, but this spot is only one-third the size of Jupiter's.

★ The winds at Saturn's equator, the most ferocious in the solar system, measure 475 m/sec (1060 mi/h). The winds decrease at higher latitudes with alternating east-west jet streams starting at the mid-latitudes of both hemispheres. Within each belt or zone, the maximum wind velocity tends to occur at the center, rather than at either edge (as was the case for Jupiter). The zonal wind patterns are nearly symmetric about the equator.

★ Saturn's atmospheric temperament is more subdued than Jupiter's. Saturn also has high pressure anti-cyclonically rotating storms, but only at mid to high latitudes. Also, while exhibiting both high- and low-latitude auroral emissions, lightning was not as globally evident as it was at Jupiter: it was observed only in low latitudes.

Saturn's Rings



★ When Galileo first turned his 30-power spyglass on Saturn in 1610, he mistook Saturn's rings for satellites. Fifty-five years later, Christian Huygens correctly identified the mysterious bumps on both sides of the planets as the tips of a ring. When the Voyagers encountered Saturn in 1980 and 1981, their true

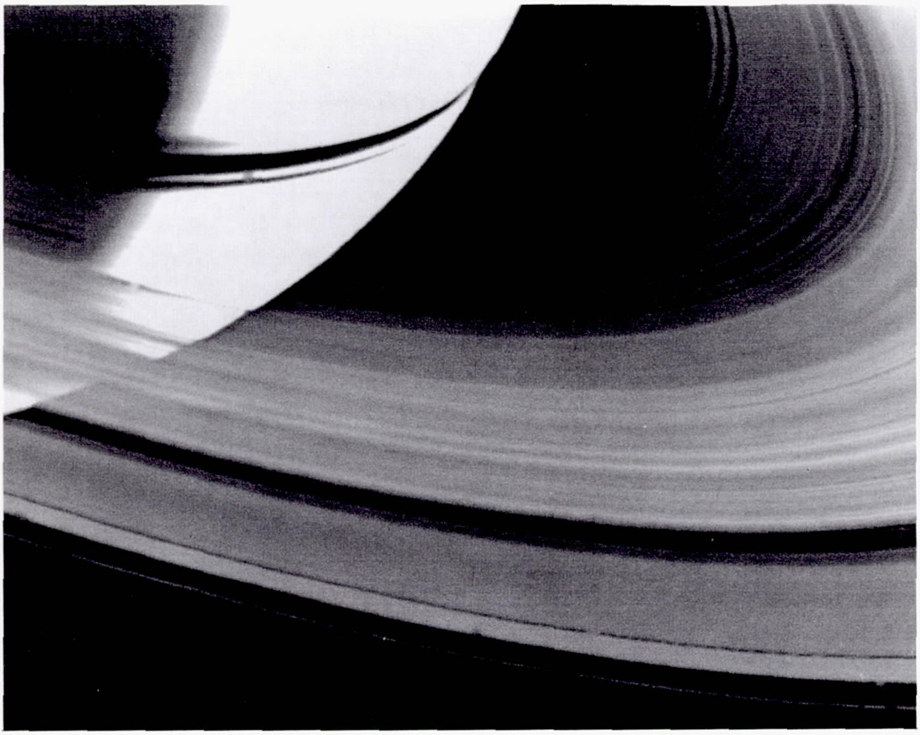


Figure 13-7. Looking back at Saturn and its rings, Voyager 1 captured this remarkable image that reveals the elaborate structure of "ringlets" and "gaplets," including the famous Cassini and Encke divisions, as well as the string-like F-ring.

splendor was finally brought home to us. The rings consist of an icy cast of trillions that march around their captor in a vast sheet of unbelievable expanse and thinness. The patterns formed within this sea of ice are both simple and complex. There are circular rings, eccentric rings, kinky rings, clumpy rings, dense rings, and gossamer rings. There are ringlets and gaplets. There are resonances, spiral density waves, spiral corrugations in the otherwise flat ring plane, spokes, shepherding moons, and almost certainly unseen moonlets orbiting within the rings. The elaborate choreography of Saturn's complex ring system is produced and orchestrated by the combined gravitational tugs of Saturn, its moons that lie out beyond the rings, and even the neighboring ring particles on each other, as well as by soft collisions between nearby bergs and particles.

★ The ring particles range in size from smaller than sugar grains to as large as houses. They are believed to resemble irregular snowballs—not as

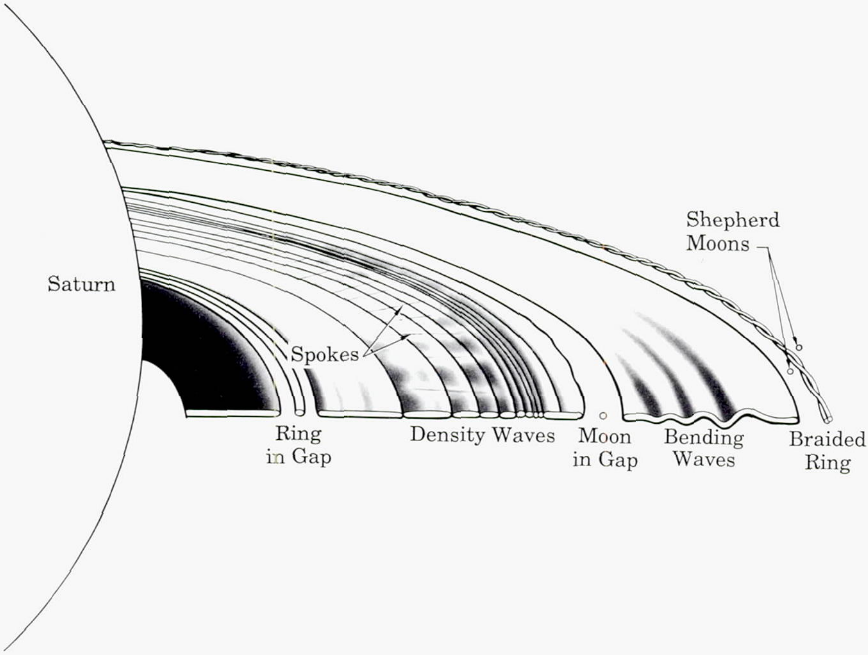
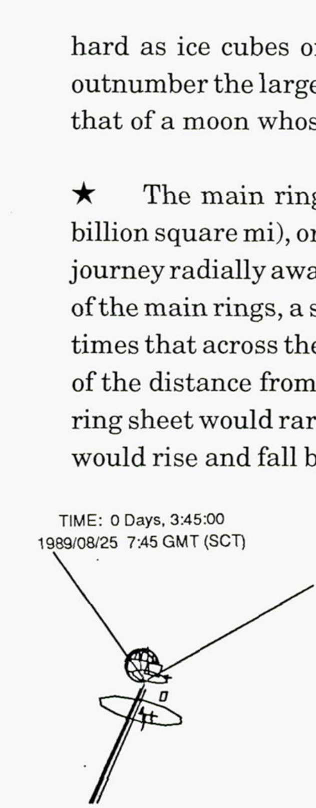


Figure 13-8. An artist's rendition portrays striking features and the startling complexity of the vast Saturnian ring system, as though woven into an intricate space tapestry.

hard as ice cubes or as fluffy as cotton candy. The smaller particles far outnumber the larger ones, but the entire mass of the rings is not more than that of a moon whose diameter is only 320 km (200 mi).

★ The main rings cover an area of just over 40 billion square km (15 billion square mi), or roughly 80 times the total surface area of the Earth! To journey radially away from Saturn from the innermost to the outermost edge of the main rings, a space traveler would need to cover a distance equal to 13 times that across the United States. Tip to tip, they span roughly 70 percent of the distance from the Earth to the Moon. However, the thickness of the ring sheet would rarely exceed 10 m (33 ft), though corrugations in the sheet would rise and fall by as much as 1.6 km (1 mi). The Saturn ring sheet is so thin that, were a scale model to be made from material as thick as a quarter, its diameter would have to be 16 km (10 mi).



★ Some scientists believe that the rings consist of primordial debris that has been unable to coalesce into proper moons because it lies within the Roche limit — the boundary separating the "safe" zone for satellites from the region where, conditions permitting, the planet's gravity can literally pull satellites apart. Others suggest that the rings are former moons that have been captured by Saturn, broken apart, further chipped away by collisions among the pieces, and spread out in a thin disk around the planet.

Still other scientists offer the most appealing explanation of all for the origin and maintenance of the rings: during the later stages of Saturn's formation, one or more moons formed outside the planet's Roche limit. But, as Saturn continued to pull in matter, the Roche limit moved out beyond these moons, which were small enough and hard enough to avoid destruction by Saturn's strong gravity. Instead, they were eventually shattered by impacts from incoming meteoroids. The latter hypothesis suggests that, even now, other "ringmoons," smaller than their ancestors but a thousand times larger than the largest ring particles, are patiently orbiting as they have been for millions of years, awaiting that moment when they too will be transformed into magnificent rings.

Saturn's Moons

★ Saturn may be the most prolific planet in the solar system, producing at least seventeen offspring, with evidence for several more. One of these, Phoebe, may actually have been a wandering stray from the asteroid belt or elsewhere that Saturn adopted into its extended family.

★ The five largest moons—Tethys, Dione, Rhea, Titan, and Iapetus—range in diameter from 1060 to 5150 km (650 to 3200 mi), and were all discovered telescopically in the seventeenth century. The eighteenth century can lay claim to Mimas (392 km or 244 mi) and Enceladus (500 km or 310 mi). By the end of the nineteenth century, Hyperion (410 by 260 by 220 km or 255 by 160 by 140 mi) and Phoebe (220 km or 140 mi), the only two satellites of Saturn which are not in locked rotation (i.e., rotating about their spin axis such that they keep their same face toward Saturn), joined the ranks. Saturn's remaining known satellites (eight total) range in diameter from 25 to 190 km (15 to 120 mi); all are non-spherical, and all are smaller than the others mentioned above. All were discovered in the twentieth century, including three discovered by Voyager 1 during its 1980 encounter with Saturn.

★ Titan, the first of Saturn's moons to be discovered (by Huygens in the early 1600s), is classified as a moon even though it is larger than Mercury. Its surface is hidden from view (except at infrared and radio wavelengths) by

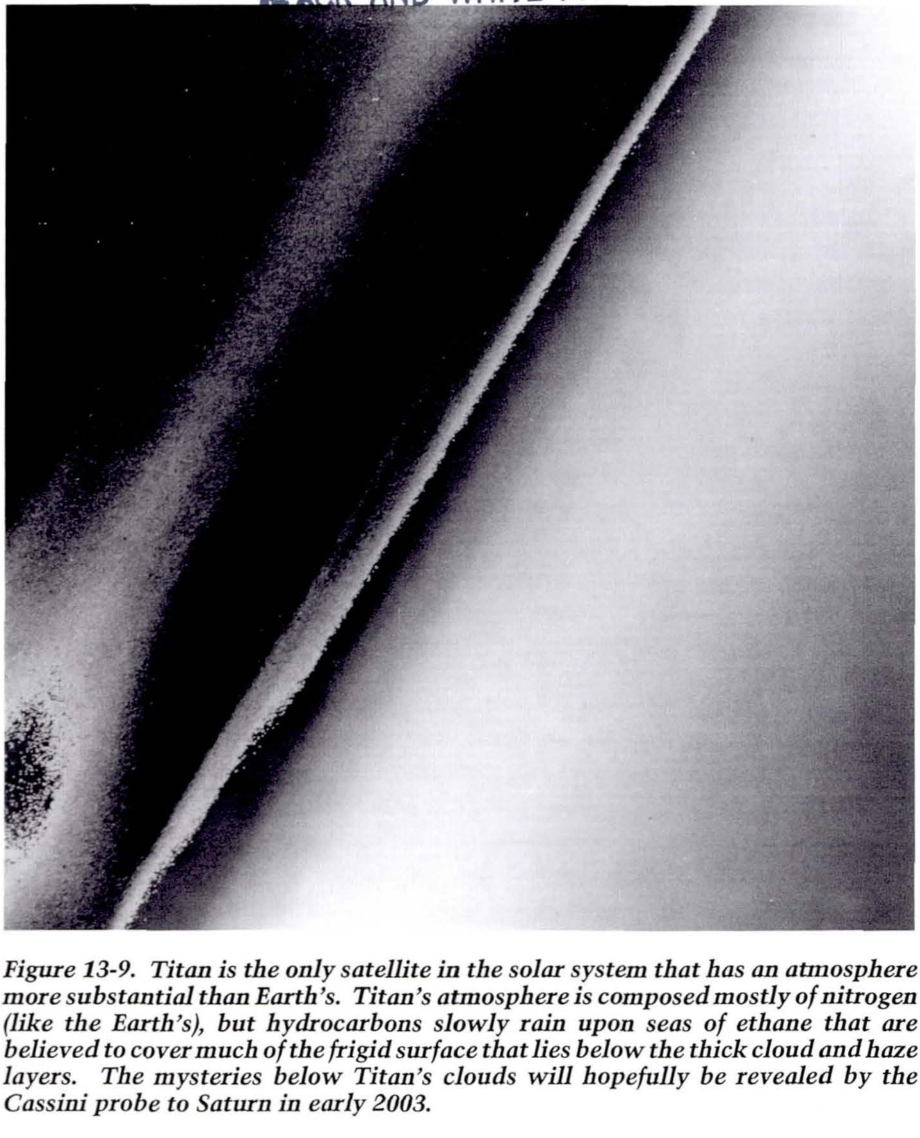
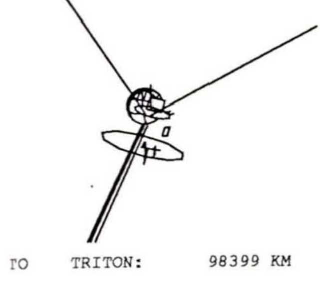


Figure 13-9. Titan is the only satellite in the solar system that has an atmosphere more substantial than Earth's. Titan's atmosphere is composed mostly of nitrogen (like the Earth's), but hydrocarbons slowly rain upon seas of ethane that are believed to cover much of the frigid surface that lies below the thick cloud and haze layers. The mysteries below Titan's clouds will hopefully be revealed by the Cassini probe to Saturn in early 2003.

a dense atmosphere. This latter characteristic makes it unique among all moons in the solar system and the subject of much scientific curiosity. Titan's primarily nitrogen atmosphere is more like Earth's than the atmospheres of Venus or Mars, which are composed primarily of carbon dioxide, or like Jupiter, Saturn, Uranus, and Neptune, which have atmospheres composed primarily of hydrogen and helium. Methane and argon are probably the other main constituents in Titan's atmosphere.



Titan might appear an interesting place to spend a holiday, since it may have an ocean covering its surface to a depth of 1 km, with islands of solid water ice rising from the ocean floor. Of course, what the travel brochure would probably fail to mention is that this "island paradise" would be atop an ocean of organic sludge of ethane, methane, and nitrogen, and that its frigid temperature of -179°C (-290°F) would be most uncomfortable.

The planned Cassini mission to Saturn in the late 1990s perhaps will end all false claims to Titan's desirability as a vacation destination when it drops a probe through Titan's thick clouds and haze to reveal, for the first time, the details of its true ambiance.

★ Tethys is one of two Saturnian satellites to be a "parent." (Dione is the other.) Tethys plays guardian to the Lagrangian satellites, Calypso and Telesto. Lagrangian satellites are small objects that, by maintaining approximately 60 degrees of arc ahead of or behind a larger parent object, can share the same orbit and orbital speed as the parent. Tethys has an unusually large impact crater (named Odysseus) on its leading hemisphere centered at about 30° north latitude.

★ Dione is distinguished by bright wispy markings that resemble thin veils covering its soft features. The veils probably were created by frost-like material formed by the explosive release of volatiles from its interior. It is estimated that all of Saturn's satellites from Dione inward were struck at least once by a body with sufficient kinetic energy to shatter the satellite. Therefore, it is likely that Dione and the inner moons have either been reassembled in orbit or are mere fragments of their former selves.

★ Most of the known moons in the solar system have certain eccentricities and unique features, but Iapetus exhibits the most split personality. Its light-to-dark contrast is the most extreme yet seen in the solar system: its dark face is as dark as an asphalt parking lot, while its light face is as white as a fresh blanket of snow. The dark surface has sharply defined edges and contains no visible impact craters, suggesting that the dark material may have formed after methane flowed from the interior. (Methane turns very black after having its carbon-hydrogen bonds broken by sunlight or radiation bombardment.)

★ Unlike high-contrast Iapetus, Phoebe is one of the darkest objects in the solar system. It is conjectured that Phoebe is a wayward asteroid that was adopted (or kidnapped) by Saturn. If so, Phoebe is the first asteroid observed in the outer solar system from a relatively nearby spacecraft. Phoebe's asteroid nature is supported by the fact it is the only Saturnian satellite in a retrograde orbit (i.e., it orbits opposite the rotation direction of the main planet). It is also inclined by about 30° with respect to Saturn's equator.

★ Hyperion is probably a mere shadow of its former self. This dark, irregularly shaped satellite is thought to be a remnant of a much larger object which was shattered by impact. It orbits about Saturn in a random-like motion described as "chaotic tumbling."

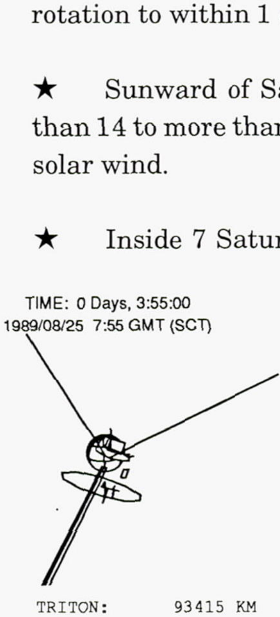
★ Although Mimas and Enceladus are similar in diameter and in proximity to Saturn, they are in marked contrast with each other. Mimas has a huge impact crater (Herschel) nearly one-third of its diameter. The crater is 10 km (6 mi) deep with a central peak rising 6 km (4 mi) from its floor. Mimas came close to being shattered by the impact that created this huge pockmark. In contrast, portions of Enceladus's surface are nearly devoid of impact craters. Enceladus shows evidence of a complex geological history unsuspected for such a small object. Enceladus may experience active water volcanism. As its orbit is coincident with the densest part of Saturn's tenuous E-ring, Enceladus may be the source of the E-ring material.

Saturn's Magnetosphere

★ Prior to the Voyager encounters, Saturn was shown by Pioneer 11 to have a magnetic field. The field is basically dipolar in nature, having well-defined north and south magnetic poles, and is aligned with Saturn's axis of rotation to within 1 degree.

★ Sunward of Saturn, the magnetopause varies in location from less than 14 to more than 30 Saturn radii*, depending upon the intensity of the solar wind.

★ Inside 7 Saturn radii there is a torus of hydrogen and oxygen ions, possibly originating from the sputtering of water ice from the surfaces of Dione and Tethys. There is also a doughnut-shaped region of neutral hydrogen atoms extending from 8 to 25 Saturn radii, which probably originated from the atmospheres of Titan or Saturn.



*Saturn's equatorial radius is 60,268 km (37,450 mi), at a pressure of 1 bar.

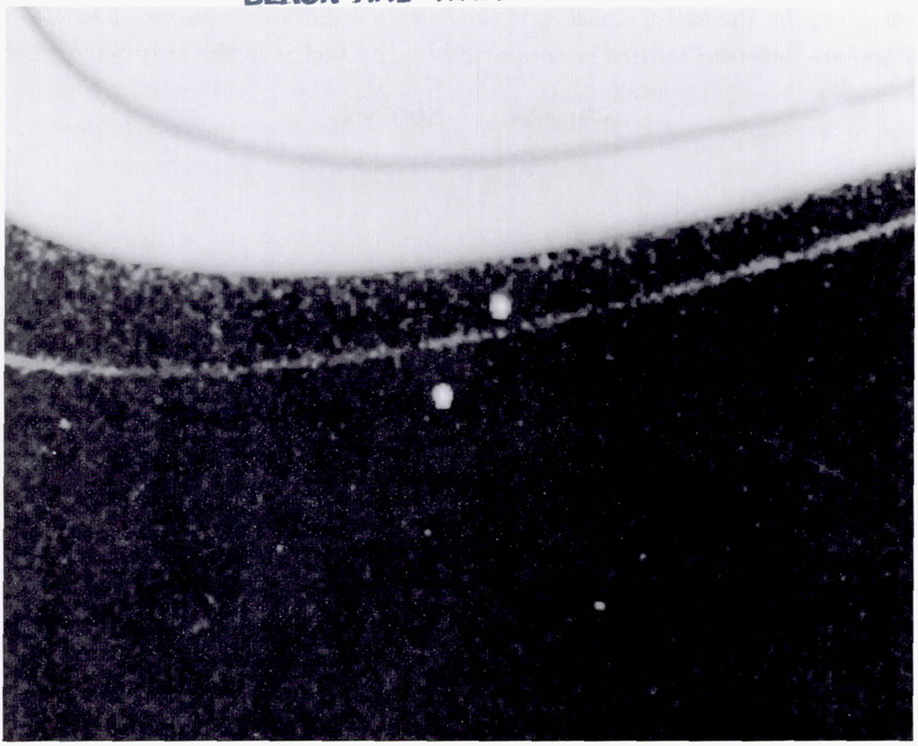


Figure 13-10. Two small satellites (Prometheus and Pandora) "shepherd" Saturn's F-ring between them. These satellites confine the ring particles into a narrow band, and may have a role in the "braiding" in the F-ring observed by Voyager 1.

Uranus

Though a variety of names were suggested for this planet shortly after its discovery in 1781, the name Uranus prevailed. In Roman mythology, Uranus was the father of Saturn, god of the sky, and husband of Earth. Now, Uranus takes on the added role of being yet another member of the planetary family.

By then a seasoned traveller, Voyager 2 began its tour of the Uranian system on November 4, 1985. For the following 3-1/2 months, and for the first time in the history of our species, Uranus provided us with some tantalizing clues as to the "sleight of hand" behind his magic.

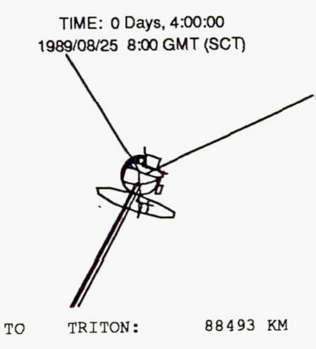
Uranus' equator is tilted 98 degrees with respect to the plane of its orbital motion about the Sun. The most widely accepted reason for this strange inclination is that the planet was struck off-center by a body roughly one to two times the size of the Earth. As this body broke up and became part of Uranus, it's suspected that it imparted enough rotational energy to the planet—which at the time was probably spinning more "right-side up"—to reorient its spin axis. This hypothesis remains conjecture, however, since other evidence for such an impacting body has not been seen anywhere in the Uranian system.

One of the more surprising outcomes of this encounter was the development of a new interior model for Uranus based upon a comparison of its longer-than-expected rotation period with its previously determined gravity field. Prior to this time, it was suggested that Uranus' interior consisted of three distinct layers: (1) a rocky core containing mostly magnesium silicates and iron, covered by (2) an "oceanic" mixture of water and other constituents, which in turn was enclosed by (3) a molecular layer consisting mostly of hydrogen. The new post-Voyager models discard previous models and propose instead a structure having a large core composed of a mixture of rock, ice, and gas, covered by a thick atmosphere of hydrogen, helium, and heavier gases. The core either has many layers with different compositions or else is characterized by a continuous density and composition gradation within the core. A very small molten "rocky" core may or may not exist at the planet's center.

In contrast to Jupiter and Saturn, Uranus has at best a weak internal heat source—less than 13 percent of its radiated heat comes from its interior. It is possible that all of its observed heat is provided by the Sun.

Uranus' Atmosphere

★ Due to Uranus' unusual inclination, the polar regions receive more sunlight during a Uranus year (84 Earth years), and scientists anticipated that its poles would be about 4°C (7°F) warmer than its equator. The Uranian winds were also expected to be different than those found at less-inclined planets such as Saturn. Instead, Voyager 2 discovered that the equatorial temperatures at Uranus are remarkably similar to temperatures at the poles (-209°C or -344°F), implying that some redistribution of heat toward the equatorial region must occur within the atmosphere. And, the wind patterns are much like Saturn's, flowing parallel to the equator in the same direction as the planet's rotation. Thus, like at Saturn, circulation patterns at Uranus are apparently determined chiefly by the effects of the planet's rotation, rather than by the distribution of sunlight on the planet.



★ Ninety-eight percent of the upper atmosphere of Uranus is composed of hydrogen and helium; the remaining 2 percent is methane. However, scientists speculate that the bulk of the lower atmosphere is composed of water (perhaps as much as 50 percent), methane, and ammonia. (Water and ammonia were

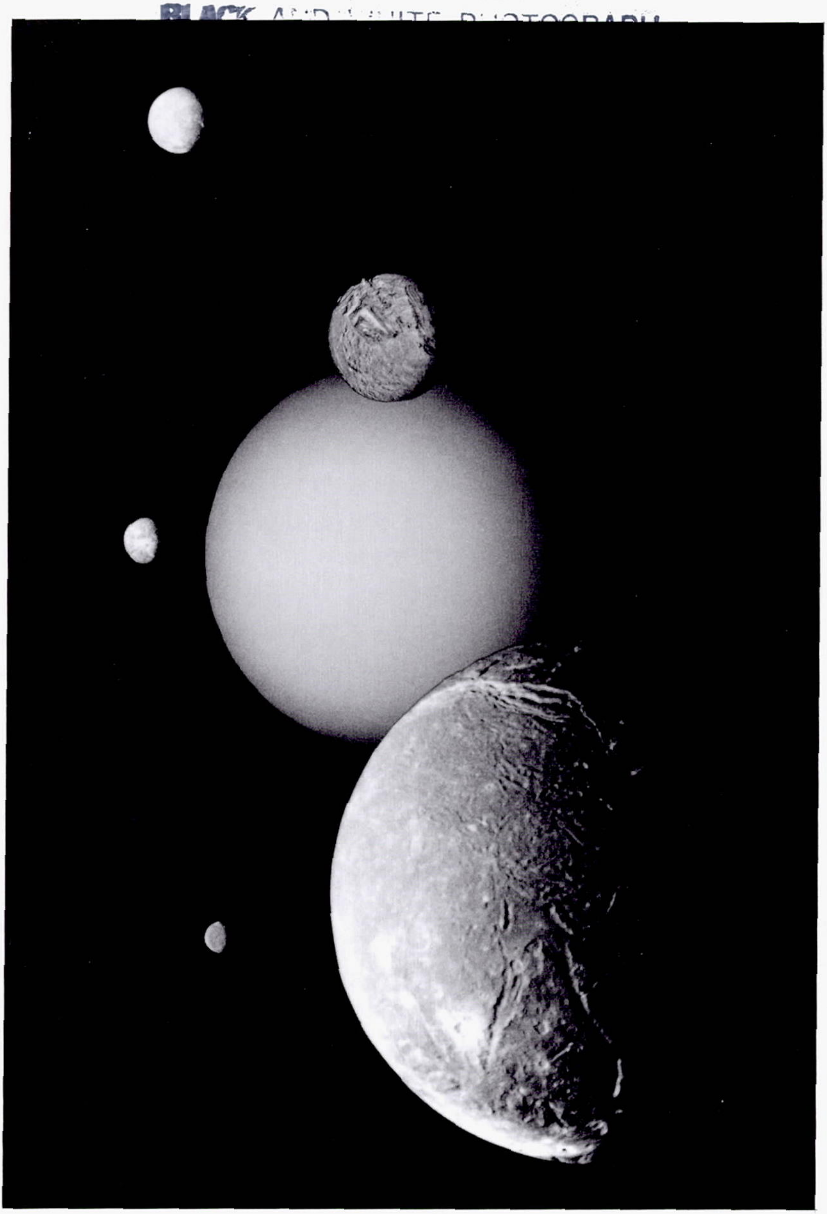


Figure 13-11. Uranus is surrounded by its five largest satellites in this montage of images from the January 1986 encounter. The planet is also encircled by eleven rings, but they are too dark to be seen in this montage.

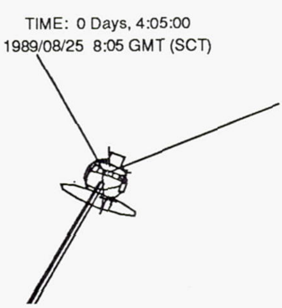
not detected during the encounter because they freeze at much deeper levels in the atmosphere than could be detected by Voyager 2.) Methane, which is responsible for Uranus' blue-green color because it selectively absorbs red sunlight, condenses to form clouds of ice crystals in the cooler, higher regions of Uranus' atmosphere. The clouds, which generally are useful in tracking the Uranian wind patterns, are optically thin and nearly featureless. Compared to the tumultuous clouds detected at Jupiter, the Uranian clouds are relatively calm, and no lightning was observed by Voyager 2.

Uranus' Rings

★ Two additional rings (and an extensive set of dust bands) were discovered during the Uranus encounter, which brings the total number of known rings to eleven. (The first nine were discovered during a star occultation event observed from Earth relatively recently, in 1977.) The rings all lie within one planetary radius* of Uranus' cloud tops. They are, in order of decreasing orbital radius from the center of the planet, epsilon, 1986U1R (the first of the newly discovered rings), delta, gamma, eta, beta, alpha, 4, 5, 6, and 1986U2R (the second of the newly discovered rings). Bands of dust-sized ring material extend inward from 1986U1R, perhaps all the way to the planet. Astronomers in India probably saw 1986U2R during the 1977 occultation event, but since no other observatory did, the claim could not be confirmed. We could say, then, that Voyager 2's "discovery" of this ring was really a confirmation.

★ Except for 1986U2R and the dust bands, Uranus' rings are all narrow, much like some of the narrow rings observed at Saturn. They range in width from 1 to 93 km (0.6 to 58 mi), and are only a few kilometers thick. The ring structure appears to vary considerably with longitude. For example, the outermost Uranian ring, epsilon, is nearly five times as wide at its most distant point from the planet as it is at its closest point.

★ The Uranian rings are colorless and extremely dark. The dark material may be either irradiated methane ice or organic-rich minerals mixed with water-impregnated, silicon-based compounds (something akin to carbon-type asteroidal material). If compressed together, the Uranian ring material would form a moon about 30 km (19 mi) across.



★ Based upon observations of the narrow rings of Saturn, it was expected that the Uranian ring system would consist of a large quantity of dust; it was a great surprise to learn that dust comprises less than 1 percent of the Uranian system. (The rings primarily

*The equatorial radius of Uranus is 25,560 km (15,880 mi), at a pressure of 1 bar.

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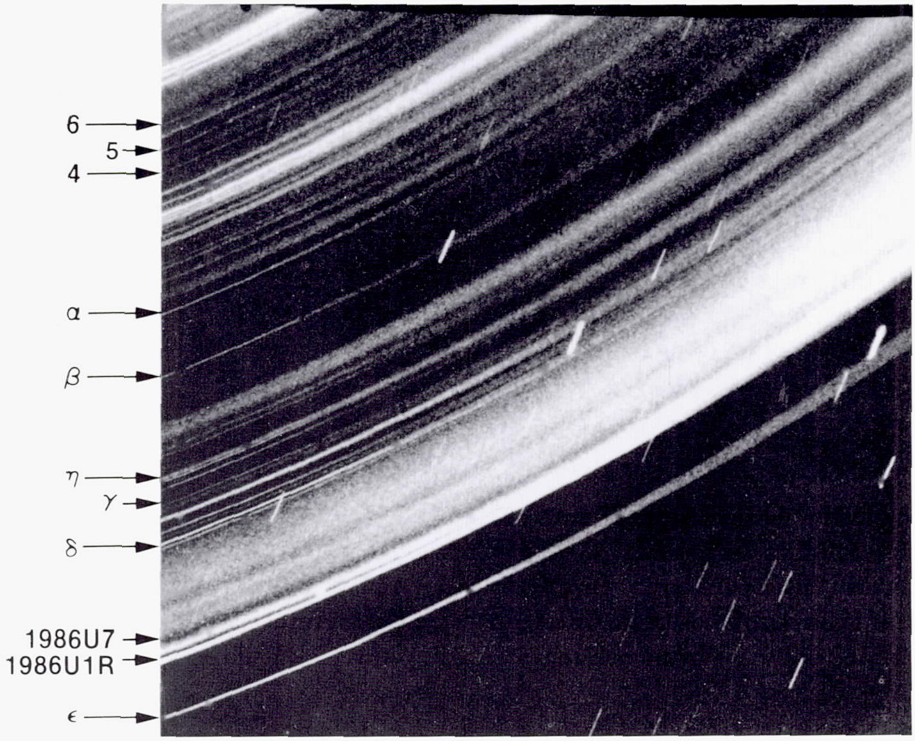


Figure 13-12. An extensive distribution of dust is seen within the Uranian ring system in this Voyager-2 image taken in forward-scattered sunlight. The short streaks are stars smeared out by Voyager 2's motion while the camera shutter was open.

consist of particles with diameters of several centimeters.) The mechanism which sweeps the rings clear of such planetary dandruff appears to be Uranus' extreme upper atmosphere, which is considerably more dense than expected. The dislodged dust particles appear to take up temporary residence in bands at or beyond 39,500 km (24,500 mi) from the center of the planet. At closer distances, the particles eventually fall into Uranus and blaze out of existence as meteorites.

★ One of the mechanisms thought to keep ring particles from drifting off into space or towards the planet is what has come to be known as shepherding. Shepherding satellites are tiny moons, first postulated to explain the Uranian rings, but first observed during Voyager 1's encounter with Saturn. They orbit close to the rings, gravitationally nudging wayward particles back inside their proper borders. Two such shepherds were imaged flanking Uranus' epsilon ring. Additional shepherding satellites were not imaged near any of the inner Uranian rings, possibly because the moons, if they exist, are too dark and/or too tiny to have been sensed by Voyager. A possible shepherd has been inferred to exist 9 km inside the eta ring based upon RSS and PPS detections of density waves in the delta ring.

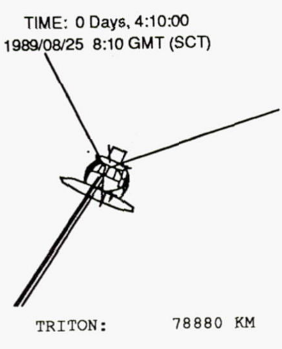
★ Incomplete rings or "ring arcs," similar to those discovered within the Encke division in Saturn's rings, may have been seen by the PPS at Uranus during the encounter. There is evidence that ring arcs exist at Neptune as well. Scientists are curious about the source of these partial rings and the mechanisms that maintain their structure. They may be transient clumps of debris arising from collisions between moons orbiting near the planet in belt-like groups, or, alternately, clumps of debris maintained in place by one or more (as yet undiscovered) moons orbiting in inclined orbits.

Uranus' Moons

★ Ten additional Uranian moons were discovered by Voyager 2, bringing the total number of known moons there to 15. In order of decreasing distance from the planet, the 15 moons are Oberon, Titania, Umbriel, Ariel, Miranda, Puck, Belinda, Cressida, Portia, Rosalind, Desdemona, Juliet, Bianca, Ophelia, and Cordelia.

The first five moons listed were discovered prior to the Voyager-2 encounter, the most recently discovered being Miranda, found by Gerard B. Kuiper in 1948. Oberon and Titania were discovered by William Herschel, the discoverer of Uranus, in 1787. Herschel may also have spotted Umbriel on April 17, 1801. The first definitive sightings of Umbriel and Ariel were reported in 1851 by the English amateur astronomer William Lassell, who had discovered Neptune's moon Triton four years earlier. There is some evidence that Ariel was first sighted by Otto Struve on October 8, 1847.

In 1852, John Herschel, William's son, borrowed names from English literature (works of Shakespeare and Pope) to name the first five known moons, breaking the tradition of using names from Greek or Roman mythology. The naming of the moons found by Voyager 2 followed the younger Herschel's precedent.



★ The two largest moons, Oberon and Titania, are less than half the diameter of Earth's moon. Both moons have average densities between 1.6 and 1.7 gm/cm^3, surprisingly high in comparison to Saturn's icy moons. Scientists anticipated that as one pro-

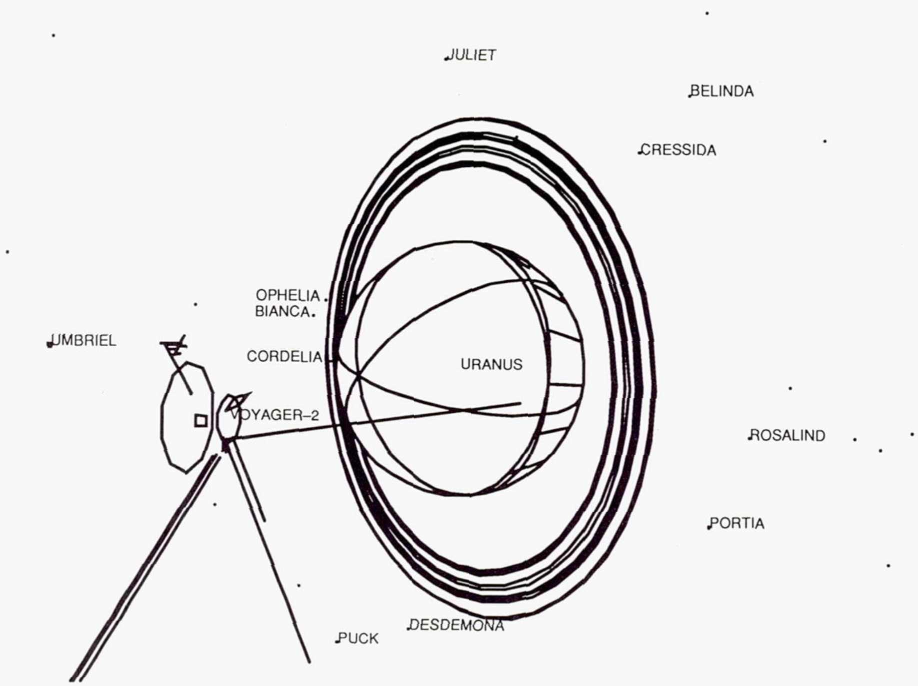


Figure 13-13. Ten newly discovered moons at Uranus in their positions between the rings and Miranda at the time three hours before Voyager 2's closest approach. (Computer graphics representation; names chosen by the International Astronomical Union [IAU].)

gressed farther from the warmth of the Sun, bodies would be icier, and thus have lower densities.

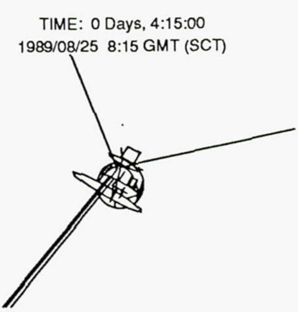
★ Titania, the reddest of Uranus' moons, may have endured global tectonics as evidenced by complex valleys and fault lines etched into its surface; smooth sections indicate that volcanic resurfacing has taken place. (All four of Uranus' largest moons have been completely resurfaced.) Titania's surface fracturing may have been caused by the expansion of frozen subsurface water. Another possible explanation for its wrinkled appearance is that at one time in its history it was blasted apart by a large impacting body and subsequently reassembled in its present orbit. Oberon, however, shows few signs of having experienced tectonic activity since visible fault lines are nearly absent on its heavily cratered surface.

★ Umbriel and Ariel are roughly three-fourths the size of Oberon and Titania. Umbriel is the darkest of Uranus' large moons (19 percent reflectance) with huge craters peppering its surface. Unlike its sisters, Umbriel has a paucity of what are known as bright ray craters, which are formed on an older, darker surface when bright submerged ice is excavated and sprayed by meteroid impacts, a process sometimes referred to as "impact gardening." One hypothesis for Umbriel's dark surface is that it is the original surface, unchanged over the eons except by infrequent large meteoroid impacts. Or, the deep gray surface on Umbriel may be due to a fairly recent coating of material from an unknown source — presumably a nearby source, since Titania and Ariel, the moons on either side of Umbriel, are not coated. A plausible candidate for such a body would be a carbon-rich satellite.

In contrast, the surface of Ariel, the brightest of the Uranian moons, is relatively free of pockmarks due to a self-repair mechanism commonly known as volcanism, which periodically erases the damage done by foreign projectiles. But this process has acted incompletely there, leaving several extremely deep (tens of km) cuts on Ariel's surface.

★ The smallest of Uranus' large moons, Miranda, was aptly described during the minutes immediately following its high-resolution debut in 1986 as "the most bizarre body in the solar system." Considering its size (only about one-sixth the diameter of Earth's Moon), Miranda has a remarkable variety of terrain: rolling, heavily cratered plains (the oldest known terrain in the Uranian system) adjoined by three huge, 200 to 300 km (120 to 180 mi) oval-to-trapezoidal regions known as coronae, which are characterized by networks of concentric canyons. The coronae, volcanic complexes named Arden, Elsinore, and Inverness, are the subject of great interest due to their complex geometry: all are much less cratered than the plains and contain an oddly oriented series of ridges, grooves, and cliffs of differing reflectances and dimensions.

What could possibly explain Miranda's bizarre surface features? One interesting hypothesis accepted by a minority of scientists is that on several occasions the moon was impacted, shattered, and haphazardly slapped back together gravitationally. The more popular hypothesis is that the surface of Miranda was breached by huge slabs of ice that rose upwards during its initial period of differentiation (settling into layers). But the differentiation process was halted before completion as the primordial heat ran out, and Miranda was left like an abandoned sculpture.



★ Nine of the new moons range in size from 26 to 108 km (16 to 67 mi) and, being closer to the planet,

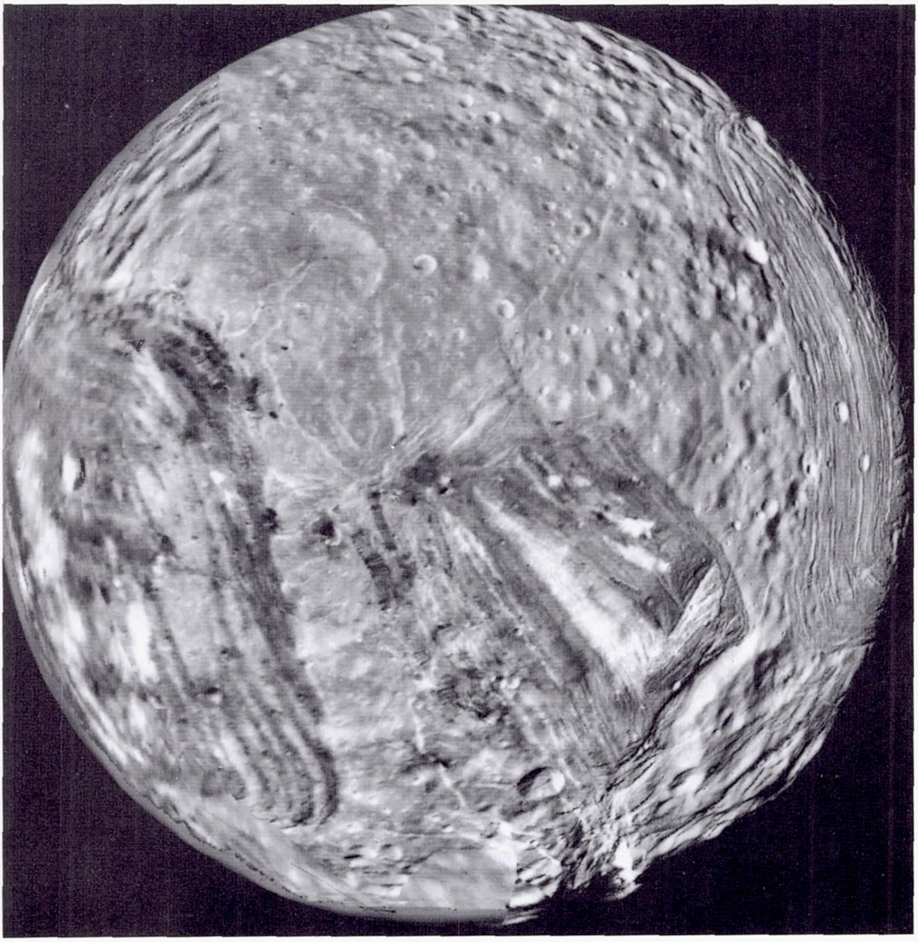


Figure 13-14. This image of Uranus' moon Miranda—the highest-resolution image ever returned by either Voyager spacecraft—shows the bizarre variety in the geology found there by Voyager 2. The smallest discernible features are less than 1 km (0.6 mi) across.

have faster periods of revolution (8 to 15 hr) than their more distant relatives. Puck, the tenth and largest new moon, and the first to be discovered by Voyager, is 154 km (96 mi) in diameter and makes a trip around Uranus every 18 hours.

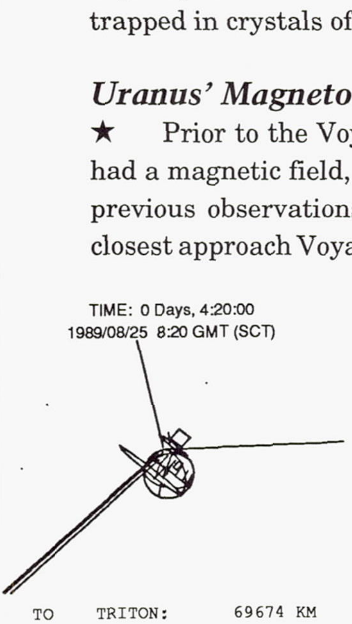
★ Two of the moons discovered by Voyager, Cordelia and Ophelia, are shepherding satellites that gravitationally constrain the outermost ring, epsilon. The other eight new moons lie between the orbits of Ophelia and Miranda.

★ Puck and Cordelia were the only two new moons whose disks were resolved in Voyager imaging; each reflects only 7 percent of the incident sunlight. Puck is shaped somewhat like a potato, with a huge impact crater marring roughly one-fourth of its surface. Compared to Puck and Cordelia, the five first-known Uranian moons are not nearly as dark—they reflect from 19 to 40 percent of the incident sunlight. They are, however, darker than their Saturnian counterparts. It is speculated that their darkness relative to Saturn's moons may be due to a surface coating of carbon-rich organic substances. This hypothesis relies on the fact that all of Uranus' moons spend a large fraction of their orbits within the magnetosphere, bombarded by energetic protons which can darken their surfaces through irradiation of the methane ice thought to comprise a large portion of each moon. Another difference between the Uranian and Saturnian moons is that Uranus' moons are brightest in areas where there are geologic features, suggesting that perhaps sub-surface ices oozed or leaked through newly formed cracks and craters.

★ For years to come, the moons of Uranus will continue to bedazzle planetary geologists. Of particular interest is how bodies the size of Miranda and Ariel could undergo tectonic and volcanic processes—once thought to be limited to large bodies which possess the capability of generating sizeable internal heat reserves. Two of the hypotheses currently being bantered about are that the requisite heat sources arise from (1) the tidal heating that occurs when a close satellite orbits its planet in an elliptical path (tidal heating is thought to be the source of geological activity on Io and Europa at Jupiter, and Enceladus at Saturn), or (2) heating from radioactive materials trapped in crystals of water ice.

Uranus' Magnetosphere

★ Prior to the Voyager-2 encounter, it was unknown whether Uranus had a magnetic field, due to the absence of nonthermal radio emissions in previous observations. To the delight of the scientists, five days before closest approach Voyager 2 discovered that a magnetic field indeed did exist at Uranus. Of great surprise was the discovery that the magnetic axis can be represented by a dipole tilted 58.6 degrees with respect to Uranus' rotation axis, by far the greatest offset seen at any of the planets with magnetic fields. (Earth's magnetic axis has the second largest inclination, 11.4 degrees; Saturn's has the



smallest, 0 degrees.) The inclination of the Uranian magnetic axis causes the field to wobble as the planet rotates.

Another misalignment discovered with regard to this field is that the magnetic center of the planet is displaced from the planet's center by 0.3 Uranian radii. (At Earth, this displacement is only 0.08 Earth radii; at Saturn, it is only 0.02 Saturnian radii.) One possible explanation for both of these anomalies is that the magnetic field is undergoing a reversal; however, this explanation, although supported by the fact the Earth has undergone several field reversals, is by no means conclusive. One hypothesis suggests that conditions in the interior of Uranus permit more rapid reorientation of the magnetic field, which may be experiencing long-term, semi-periodic tumbling.

★ The magnetosphere is formed into a giant wind-sock shape around Uranus by the incoming solar wind, with a huge tail at least 42 times longer than Uranus' radius extending from the planet's dark side. The magnetotail is very similar to Earth's. In fact, other than its high tilt and large offset,

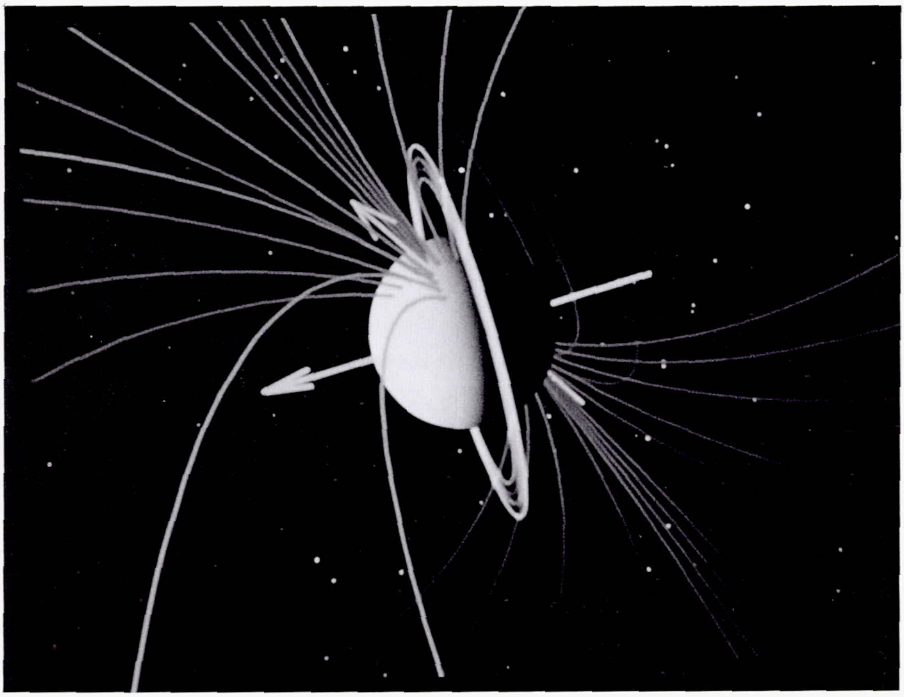


Figure 13-15. A computer-graphics reconstruction of the surprising orientation of Uranus' magnetic field. The planet's spin axis is shown pointing towards the Sun to the left; the north pole of the magnetic dipole points to the upper left.

Uranus' entire magnetosphere appears to be more Earth-like than Jupiter's or Saturn's. Another feature Uranus' magnetosphere shares with Earth's is the presence of radiation belts (Van Allen belts), which are concentrated regions of high-energy charged particles.

Cruise Science Results

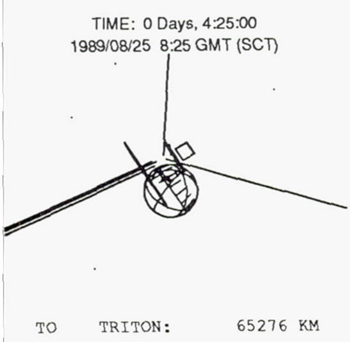
Like the Olympics, the Voyagers' planetary encounters have provided the public with an exhilarating experience that comes but once every several years. Like the Olympic torch, the Voyagers have fired our imaginations, and like the Olympic athlete, the Voyagers have no respite between their brief moments of sublimity.

The cruise phase of the Voyager missions is not as restful as the word "cruise" may imply. Both Voyagers have made a multitude of important scientific observations during these periods. Few spacecraft have ventured beyond the inner solar system (only Pioneers 10 and 11 besides the Voyagers), so the Voyagers have provided information regarding the far "outback" which otherwise would be lacking.

During cruise the Voyagers primarily perform research in three areas: (1) ultraviolet observations of both stars and the interstellar medium using the Ultraviolet Spectrometer (UVS), (2) asteroid-belt dust and planetary atmosphere observations with the Imaging Science Subsystem (ISS), and (3) fields and particles research, employing a variety of Voyager instruments.

Ultraviolet Observations

Stellar observations in the extreme ultraviolet (EUV) wavelengths from 500 to 912 angstroms and the far ultraviolet (FUV) wavelengths from 912 to 1200 angstroms are routinely performed during cruise with Voyager's UVS. The only other methods currently available for ultraviolet research employ aging Earth-orbiting spacecraft (such as the International Ultraviolet Explorer, or IUE), sounding rockets, and balloon-borne instruments, but these instruments do not cover the EUV part of the spectrum (until the Extreme Ultraviolet Explorer satellite, or EUVE, is launched in 1991). Using data from its deep-space perspective, Voyager has caused us to ask more questions than we have been able to answer. The pieces of the UV puzzle don't quite fit like we expected.



★ White dwarfs represent the senior citizens of relatively small stars (up to about 5 times the mass of the Sun). Having spent the last several billion years consuming its nuclear-energy resources, the white dwarf has gradually contracted to a body about the size of the Earth while retaining a significant fraction of its original mass. The Voyagers have provided temperature and atmospheric readings for many members of this stellar community. The temperatures of the newest residents exceed by as much as 70,000°C (126,000°F) the thermal energy that can be accurately measured from Earth. Also, severe constraints on the radius and temperature of Sirius B, the white dwarf companion to Sirius (the brightest star visible to the naked eye from Earth's northern hemisphere), have been provided by Voyager during cruise, in conjunction with observations by an X-ray satellite named XOSAT.

★ Another class of stars observed by Voyager during cruise is the Beta Cepheid variables. The distinctive feature of these hot stars is that from four to six times a day their brightnesses vary. Only Voyager has been able to accurately measure their energy distributions, since the majority of the radiation they emit is in the EUV band.

★ Cataclysmic variables, as the name implies, also exhibit varying degrees of brightness. However, unlike the Beta Cepheid variables, the Cataclysmics are binary star systems, flaring more brilliantly and far less frequently than the Beta Cepheids. Voyager observations have disproved hypotheses that proposed strong EUV and FUV emissions during these outbursts, and support hypotheses that suggest that these outbursts originate from a disk of material orbiting the white dwarf member of the system.

★ Stellar observations with Voyager's UVS additionally have provided information regarding the variability of (1) many O-type (hottest) and B-type (second hottest) stars, (2) the physical conditions prevailing in and the mechanisms behind the gaseous envelopes surrounding B-type stars, (3) supernova remnants including the Cygnus Loop, which represents the remnant of a star that exploded 50,000 years ago in the constellation Cygnus, and (4) the influence of the Sun on both the Earth and planetary atmospheres through Voyager's monitoring of solar EUV/FUV variations.

★ The UVS on Voyager has provided the best measurements on the FUV component of the interstellar radiation field which originated in the early universe. The density, temperature, and electrical state of the local interstellar material and the scattering properties of interstellar dust have been the subject of UVS cruise observations as well.

★ Also, the UVS has observed objects beyond the Milky Way during cruise, including quasars, the brightest and most distant known objects in the universe. To explain the immense amount of radiation coming from the quasars, it has been suggested that a massive black hole is situated at the center of each quasar, which is in turn located within a galactic core.

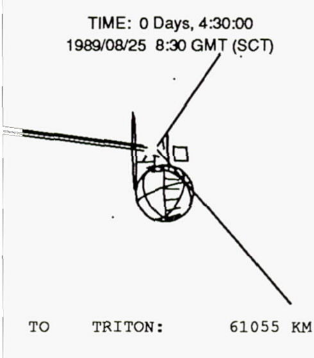
Imaging Science

★ In late 1983, the Earth-orbiting Infrared Astronomical Satellite (IRAS) discovered bands of dust encircling the solar system immediately above and below the ecliptic plane. Further analysis revealed that the bands are actually doughnut-shaped (vs. disk-shaped) due to influences on the particles' orbits arising from Jupiter's gravitational pull. It is speculated that the bands consist of roughly 5 trillion tons of pulverized asteroidal material resulting from collisions within the asteroid belt. Observations of forward scattering of the dust particles by Voyager 1's wide-angle camera have provided upper limits on the thickness and total area of the dust bands; these data support estimates derived from the IRAS data.

★ Voyager imaging of Jupiter, Saturn, Uranus, and Neptune at different phase angles has provided invaluable information regarding the outer planets' internal heat sources. Unlike the terrestrial planets, the outer planets do not radiate roughly the same amount of energy as they absorb from incoming sunlight. More than 88 percent of the heat emanating from Uranus, 56 percent of the heat from Saturn, 60 percent of the heat from Jupiter, and (possibly) 48 percent of the heat emanating from Neptune comes from the Sun. These observations have defined the variation of each planet's brightness as the angle of the illuminating sunlight varies. Information about their internal heat has important implications for the origin, evolution, internal structure, and meteorology of the outer planets.

Fields and Particles Research

★ During cruise, the Voyagers have participated with Pioneers 10 and 11 in gathering information regarding the heliosphere in the distant reaches of the solar system (all four spacecraft are currently beyond 28 times the Sun-to-Earth distance). The heliosphere is the region around our Sun which is dominated by the solar wind. The solar wind, consisting of super-heated (roughly 100,000°C, or 180,000°F) ionized gases, travels outward from the solar corona at approximately 400 km/sec (864,000 mph). Thus



far, Voyager observations have shown that the solar wind speed is constant to at least Uranus' orbit in one direction; Pioneer 10 has shown that it is constant to at least that far in the opposite direction. The solar magnetic field eventually forms into a spiral due to the rotational effects of the Sun, much like the pattern that emanates from a rotating sprinkler head.

★ As the solar wind continues its journey beyond the Sun, its structure and dynamics evolve. At a distance of 50 to 150 times the Sun-Earth distance, the solar wind finally slows to subsonic speeds and interacts more intimately with the Sun's magnetic field, which interacts with the "stellar winds" from nearby stars. When the pressures of the solar wind and interstellar plasmas are equal, a relatively thin boundary region, known as the "heliopause", forms. Since 1979, both Voyagers have detected certain low-frequency interplanetary radio emissions which indicate that they are approaching some type of boundary that may be as close as the outer reaches of Pluto's orbit. This boundary may represent the "terminal shock," the region in which shock waves are created from the initial interaction of the placid interstellar medium with the supersonic solar wind. Data obtained from the spacecraft when they finally enter this region will expand our limited knowledge of the characteristics of the shock geometry as well as place an accurate limit on the size of the heliosphere.

★ The data obtained by the spacecraft during cruise have greatly enhanced our understanding of not only the dimensions of the heliosphere and the structure of the interplanetary medium, but also the character and transport of energetic particles originating from outside the solar system. Cosmic rays traveling at significant fractions of the speed of light enter the heliosphere and interact with the Sun's magnetic field. The Voyager energetic particle experiments have measured the variation in the galactic cosmic ray intensity as the spacecraft has moved away from the Sun. These results can be used to infer, in principle, the distance to the heliopause.

★ The research the Voyagers have performed during cruise will continue during the Voyager Interstellar Mission (VIM), as discussed in Chapter 12. The body of knowledge created by Voyager observations will not only provide a better understanding of the heliosphere, but also the interstellar/galactic environment, within which the heliosphere, and humanity, reside.

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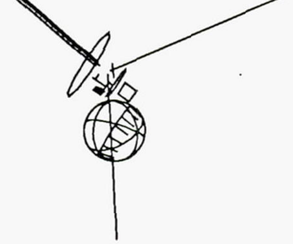

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Good-night, good-night! Parting is such sweet sorrow, that I shall say good-night till it be morrow.

William Shakespeare

14. VOYAGER REMEMBERED

The Voyager mission and its many exciting discoveries have touched the minds, imaginations, and hearts of many people. The greatest impact has probably been felt by those Voyager personnel who have dedicated a large fraction of their professional careers to making Voyager a successful mission of exploration. These are the people who have worried about Voyager each day, for many years, often outside of the normal eight-hour work shift, sometimes awaking during the wee hours to jot down an item to check out the next day.

Voyager has also touched the thoughts and lives of artists, writers, educators, and many others who have followed the mission's progress through articles in popular magazines and newspapers. Many of these people are widely known, and they too feel strongly about the Voyager achievements and the future hopes spawned by these two intrepid robots.

Therefore, several people were invited to reflect upon the meaning of the Voyager mission, but they were limited to several dozen words or less. Furthermore, as it was not practical to contact the more than 3000 people who have worked on the Voyager mission at some time over the past 17 years, it was necessary to choose several of their leaders to act as spokespeople. Outside of the Voyager Project, several well-known people were also invited to express their reflections in this chapter of the Guide. Without further ado, arranged alphabetically by contributor, the following quotes are offered:

Voyager Personnel

This fall, almost exactly twelve years after launch, Voyager will make its last planetary encounter. For all of the experimenters the mission has represented a unique opportunity for exploratory research in his or her chosen field of planetary science. It is also a demonstration of a unique collaboration between the scientific community and JPL and the ability of this combination to exploit fully a one-time scientific opportunity to explore the outer planets.

Herb Bridge
Principal Investigator
Plasma Investigation

Voyager and its successes have been a direct result of capable, dedicated people operating in a unique team environment. I credit Bud Schurmeier with creating the Voyager team spirit through his careful, deliberate selection of the original team members and his attention to developing the team spirit with his management of the Project. It was a pleasure to have worked <u>*with*</u> *Bud Schurmeier on Voyager. It has been a credit to subsequent Project Managers that the team spirit and the excellence of the effort have been sustained.*

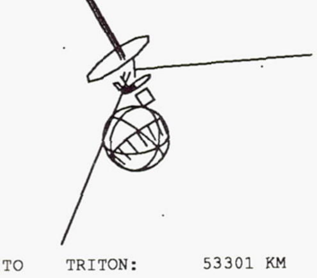
Ray Heacock
Project Manager
1979-1981

Even in hindsight, I would change not one whit of the Voyager experience. Dreams and sweat carried it off. But most of all, its legacy makes us all Earth travelers among the stars.

Charley Kohlhase
Mission Planning Manager
1975-1989

How was I to know as a kid growing up on a Greek island and watching the planets in the clear, dark sky that some day I would be part of the select group of people from Earth that put together the mission to take a close-up look at four of the five outer planets? This has to be the stuff that dreams are made of!

Tom Krimigis
Principal Investigator
Low-Energy Charged Particle Investigation



I have no desire to do much else except to ride this thing all the way out into interstellar space.

Dick Laeser
Mission Director
1974-1982
Project Manager
1982-1986

To me, the Voyager Project epitomized the salient and best features of America as a country and democratic society. The Project was conceived and implemented during the most vigorous and healthiest days of the national space effort. Some of the most creative and imaginative personnel were given the well-defined goal to advantageously utilize a unique celestial circumstance of planetary alignment which permitted realizing a goal previously thought about only in science fiction, namely "A Grand Tour of the Four Giant Outer Planets: Jupiter, Saturn, Uranus, and Neptune."

Truly, the Voyager can be considered to have been the scientific space mission of a lifetime! All of us associated with the Project share in its glory, as does the United States. I take this opportunity also to recognize the many dedicated workers, whose tender loving care created such a unique artifact with which to extend the senses of mankind in our universal search for truth and understanding.

Norman Ness
Principal Investigator
Magnetic Fields Investigation

From the very beginning, Voyager had a very special aspect to it: a uniqueness, a challenge, a promise, an appeal that has made it a never-to-be-forgotten experience for those of us who have had the good fortune to be closely involved. It was born out of adversity but, as time has now proven, it was very solidly based and exceedingly well-conceived.

Bob Parks
Project Manager
1977-1979

In 1971, when we started work on the Grand Tour missions, we had the dream of exploring all the outer planets by the end of the 1980s. Voyager and the skill, ingenuity, and resourcefulness of the people involved are about to make ninety percent of that dream come true.

Bud Schurmeier
Project Manager
1972-1976

Although we realized that Voyager was embarking on a unique journey of exploration in 1977, none of us expected the wealth of discovery that followed. Voyager revealed new worlds in which familiar features appeared with unexpected diversity that challenged our understanding and expanded our view of the Solar System.

Edward Stone
Project Scientist
1972-

In 1980 Voyager demonstrated elegantly that Saturn can be called the electrostatic giant planet. Its powerful and puzzling discharges are without parallel among the many exotic radio sources in space. How does Saturn energize its sources? Voyager produced this surprising and wonderful question. Don't ignore it amid Voyager fanfares.

Jim Warwick
Principal Investigator
Planetary Radio Astronomy Investigation

Those Known Widely

Voyager—this modern Odysseus has uncovered the unimagined intricacy and awesome spectacle of the giant planets of our own home solar system.

Neil Armstrong
Astronaut and
First Man on Moon

Lots of science has come from Voyager. But more vital is that Voyager has shown us sights that had never before been seen, and thereby reminds us how much more remains unseen and unknown. It showed us how diverse worlds can be—and that's something every person on Earth should know.

Richard Berry
Editor-in-Chief
Astronomy Magazine

Neptune!
We conquerors come
But not to conquer
Just to see,
What you are now
And what you used to be.
We touch you with our sensor-
Robot eyes,
And wander swiftly down your
alien skies,
To weigh your body, face, your
shape and size.
Then turn to show the world
Your wondrous parts,
And so you'll conquered be,
But in our hearts.

Ray Bradbury
Author

Voyager is important, because to have the means to find out "'what's out there," and not use it, is unthinkable.

Angie Dickinson
Actress

The Voyager spacecraft leave the solar system the greatest Earthborn explorers of all time. Even after their last radio link with Earth is severed, they will carry our technology, our spirit, and our music to the stars. The most awesome part of their mission is just beginning.

Jon Lomberg
Artist

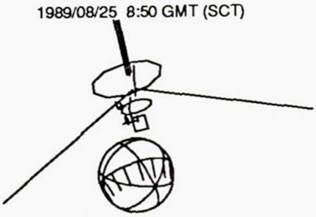
Voyager 2 will leave the classic boundaries of our solar system in August of this year, leaving behind a twelve-year legacy of knowledge and continuing on as a consummate tribute to the imagination of its designers. As this fragile yet incredible speck of twentieth century technology sweeps on into interstellar space, it carries on board the precious cargo of human aspirations for the future.

Syd Mead
Artist

Through Voyager the human intellect has extended its horizons to the farthest reaches of the Solar System, initiating a new Age of Discovery, and giving mankind a deeper insight into the role of intelligence in the Universe.

Thomas Paine
NASA Administrator
1969-1970

TIME: 0 Days, 4:50:00
1989/08/25 8:50 GMT (SCT)



TO TRITON: 46842 KM

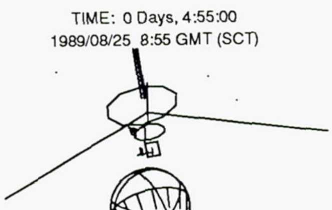
The Voyager spacecraft have completed the preliminary reconnaissance of the planetary part of the solar system. They have examined for the first time dozens of new worlds, worlds our descendants will walk upon. That can only happen once in human history. It is our good fortune that it happened in our time, and that we were able to participate in this historic voyage of exploration and discovery.

Voyager also represents, on its golden phonograph records, a hopeful—indeed, positively cheerful—message from the human species to other civilizations, if such exist, in the Milky Way galaxy. My wife, Ann Druyan, and I are especially happy to have helped design a message that will outlast our civilization and our species.

Carl Sagan
Professor of Astronomy
Cornell University

I have, indeed, been thrilled with the outstanding successes of the Voyager missions.

Clyde Tombaugh
Astronomer and
Discoverer of Pluto



TO TRITON: 44279 KM

Two roads diverged in a wood, and I—I took the one less traveled by, and that has made all the difference.
Robert Frost

15. WHO'S ON FIRST?

The Voyager successes at Jupiter, Saturn, and Uranus would never have happened without the extra-special efforts of many dedicated people, and the same will be true for Voyager's future at Neptune and beyond. During the Neptune encounter, there will be some 300 people directly supporting the Project, as well as many more around the world (see Chapter 3) that help us communicate with the two Voyagers.

The purpose of this chapter is to identify several key people associated with the various Project functional areas. After all, if you were planning a tour of Europe, there would always be a number of questions not covered in your trip brochure. You would naturally consult one of the trip leaders for answers to your special questions.

An effort has been made in Table 15-1 to identify the most basic functional areas and the appropriate cognizant personnel. It is always difficult to select a few specific individuals when so many people are associated with Voyager, but a line must inevitably be drawn somewhere. When using Table 15-1, it is assumed that any cognizant person for a given functional area can answer questions for those subareas contained to the right of the given area. For those of you who wish to see the complete Project organization, Table 15-2 has been provided.

During the actual encounter, the JPL Public Information Office will, of course, answer questions from outside people, or will generally refer these questions to one or more of the people listed in Table 15-1.

Table 15-1. Key Voyager Personnel

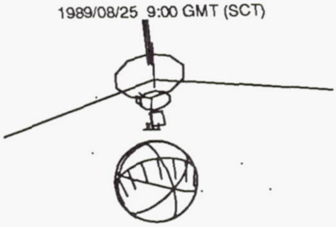
<table>
<tr><td rowspan="14">Overall Project

N. Haynes
G. Textor
C. Kohlhase
R. Rudd
D. Griffith</td><td colspan="3">Voyager Operations Functions</td></tr>
<tr><td rowspan="2">Science

E. Stone
E. Miner
P. deVries</td><td>Principal Investigators</td><td>J. Belcher (PLS)
L. Broadfoot (UVS)
B. Conrath (IRIS)
D. Gurnett (PWS)
T. Krimigis (LECP)
A. Lane (PPS)
N. Ness (MAG)
B. Smith (ISS)
E. Stone (CRS)
L. Tyler (RSS)
J. Warwick (PRA)</td></tr>
<tr><td>Science Planning and Operations</td><td>P. Doms
D. Finnerty</td></tr>
<tr><td rowspan="3">Engineering

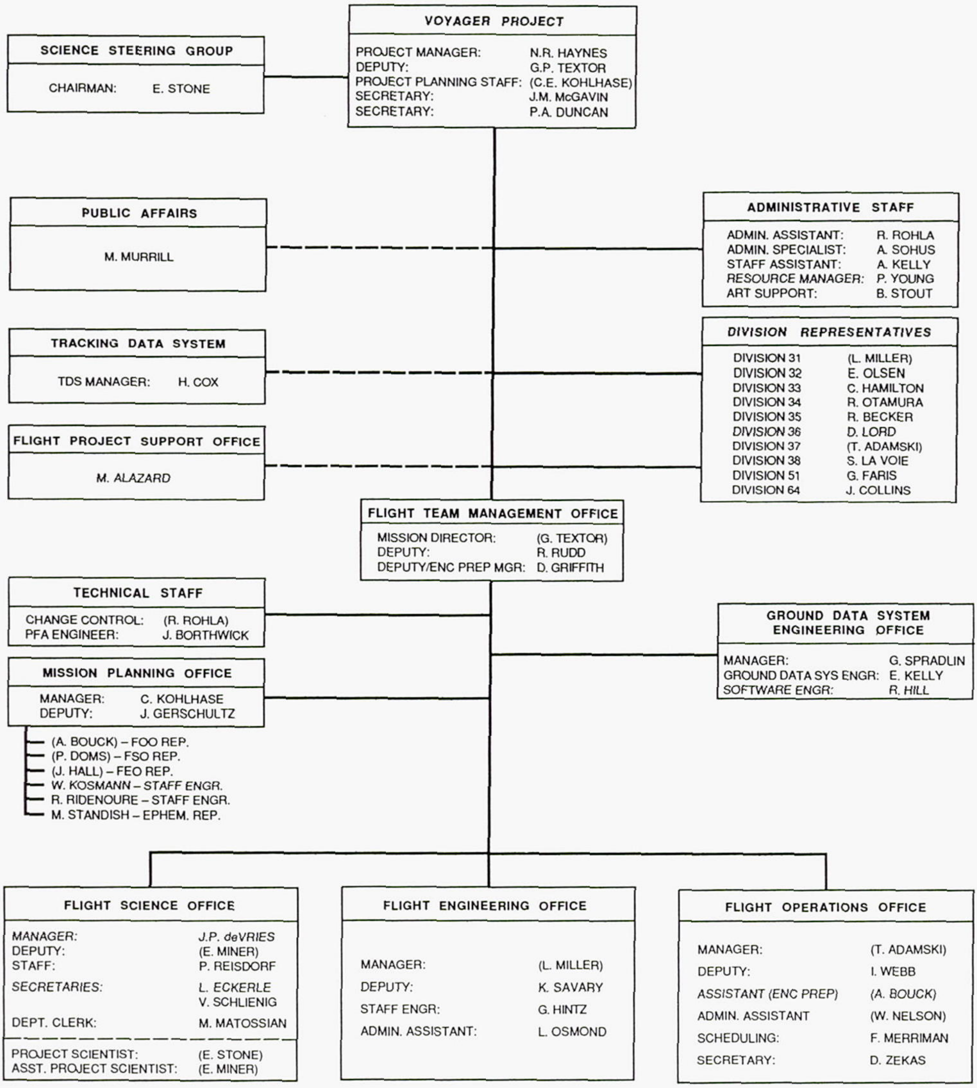
L. Miller
K. Savary
G. Hintz</td><td>Spacecraft</td><td>H. Marderness
J. Hall</td></tr>
<tr><td>Sequencing</td><td>M. Deutsch
K. Weld</td></tr>
<tr><td>Navigation</td><td>D. Gray</td></tr>
<tr><td rowspan="3">Operations

T. Adamski
I. Webb</td><td>Mission Control</td><td>J. Nash</td></tr>
<tr><td>Multimission Tracking Network</td><td>J. Jones
C. Finley</td></tr>
<tr><td>Multimission Control Center</td><td>C. Brower
E. Campos</td></tr>
<tr><td colspan="3">Voyager Mission Planning</td></tr>
<tr><td colspan="3">C. Kohlhase, J. Gerschultz</td></tr>
<tr><td colspan="3">Voyager Data System Development</td></tr>
<tr><td>Spacecraft</td><td colspan="2">M. Urban, R. Ellis, R. Otamura</td></tr>
<tr><td>Ground</td><td colspan="2">G. Spradlin, E. Kelly, R. Hill, S. Howard</td></tr>
</table>



TO TRITON: 42273 KM

Table 15-2. Voyager Project Organization



( ) = MULTIPLE APPEARANCES

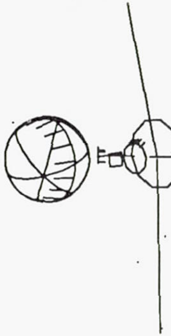


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Table 15-2. Voyager Project Organization (Continued)

GROUND DATA SYSTEM ENGINEERING OFFICE

MANAGER:	G. SPRADLIN
GROUND DATA SYS ENGR:	(E. KELLY)
SOFTWARE ENGR:	R. HILL

PROJECT DEVELOPMENT

SEQUENCE SOFTWARE
- A. DEVAULT – SEQGEN COG PROG
- J. FREEMAN – POINTER COG ENGR/PROG
- (S. LEVER) – COMSIM COG ENGR
- G. MASTERS – SYS ENGR
- K. OSLUND – SEQGEN COG ENGR
- (G. WELCH) – COMSIM/OPSGEN COG PROG

NAVIGATION SOFTWARE
- J. EKELUND – SYS ENGR

DATA RECORDS SOFTWARE
- (N. TOY) – SYS ENGR

SPACECRAFT ANALYSIS SOFTWARE
- (V. WAGNER) – S/C ANAL SYS ENGR

INSTITUTIONAL DEVELOPMENT

MCCC TELEMETRY
- P. ANDERSON – TTS COG PROG
- M. LEVESQUE – SYS ENGR
- P. HARMON – DACS TEST ENGR
- (R. HUNGERFORD) – NERT COG ENGR
- J. RITTER – TTS PROG
- B. WILKINSON – DACS COG PROG

TRACKING
- C. VEGOS – SYS ENGR

MCCC SIMULATION
- R. BIGELOW – COG PROG
- (P. HARMON) – TEST ENGR
- D. RICHARDSON – SYS ENGR

MCCC COMMAND
- R. CHEN – COG PROG
- (D. RICHARDSON) – SYS ENGR

- L. WU – TEST ENGR

RADIO SCIENCE
- A. KURSINSKI – SYS ENGR

IMAGING
- (C. AVIS) – COG ENGR
- (D. LYNN) – TEST ENGR
- N. SIRRI – IMPL MGR
- P. ZAMANI – COG PROG

DATA RECORDS
- E. BEYER – COG ENGR
- J. FOSTER – COG PROG
- (M. ORR) – TEST ENGR
- J. SPRINGER – S/W SYS ENGR

SOFTWARE CONFIGURATION CONTROL
- M. DAWSON – S/W CONFIGURATION CONTROL GROUP LEADER
- VNESSA: S. BURLEIGH – COG PROG
  L. LEE – COG PROG
  (P. LIGGETT) – IMPL MNGR

GROUND DATA SYSTEM STAFF

TELEMETRY
- (D. GILMORE) – COG ENGR
- S. HOWARD – SYSTEM ENGR

SIMULATION
- D. GILMORE – SYSTEM ENGR

COMMAND/STAFF ENGR
- M. VARUNA – SYSTEM ENGR

INTEG AND TEST
- (E. KELLY) – GDS INTEG ENGR

CONFIGURATION MANAGEMENT
- P. LAUBERT – S/W DATA ANALYST

( ) = MULTIPLE APPEARANCES

Table 15-2. *Voyager Project Organization (Continued)*

FLIGHT SCIENCE OFFICE

MANAGER:	J.P. deVRIES
DEPUTY:	(E. MINER)
STAFF:	P. REISDORF
SECRETARIES:	A. LAW L. ECKERLE V. SCHLEINIG
DEPT. CLERK:	M. MATOSSIAN
PROJECT SCIENTIST:	E. STONE
ASST. PROJECT SCIENTIST:	E. MINER

IMAGING SCIENCE DATA TEAM

CHIEF: J. ANDERSON

- (C. AVIS) – MIPS COG ENG
- V. BARLOW – DATA TECH
- S. BENSKIN – PHOTOLAB ASST OPS COORD
- S. BRESSEL – DATA MANAGEMENT COORD
- D. DEATS – MPSF OPS COORD
- J. HEWITT – PHOTO SERVICES COORD
- C. LeVINE – SCIENCE ANALYST
- D. LYNN – REALTIME ENG
- P. LYNN – DATA TECH
- G. MADRID – REALTIME ANALYST
- H. MORTENSEN – SYSTEMATIC ENG
- R. POST – PHOTOLAB OPS COORD
- R. SAUL – MPSF ASST OPS COORD
- (E. SIMIEN) – IMAGE LIBRARIAN
- C. STANLEY – SCIENCE ANALYST
- J. YOSHIMIZU – SCIENCE ANALYST
- TBD – SYSTEMATIC ANALYST
- TBD – IMAGING LIBRARY ASST
- TBD – DATA TECH

SCIENCE INVESTIGATIONS SUPPORT TEAM

CHIEF: P. DOMS

DEPUTY: D. FINNERTY

- CRS INVESTIGATORS
- IRIS INVESTIGATORS
- ISS INVESTIGATORS
- LECP INVESTIGATORS
- MAG INVESTIGATORS
- PLS INVESTIGATORS
- PPS INVESTIGATORS
- PRA INVESTIGATORS
- PWS INVESTIGATORS
- RSS INVESTIGATORS
- UVS INVESTIGATORS

- R. AUSTIN – T&T COORD
- D. BLISS – PPS AER
- K. BOLLINGER – ISS AER
- (S. BORUTZKI) – RSS ER
- J. CISNEROS – ISS DATA TECH
- (M. DELITSKY) – RSS AER
- O. DIVERS – F&P ER
- M. FONG – F&P AER
- C. HANSEN – ISS ER
- A. HARCH – SCI OPS COORD
- L. HORN – IRIS ER
- S. LINICK – UVS ER
- J. MARTIN – S/W SYS ENG
- R. NELSON – PPS ER
- J. OSORNIA – PRGMR/COMPUTER OPS
- R. POYNTER – PRA/PWS ER
- D. RUDY – ISS WORKSTATION SUPPORT
- P. SCHULTE – SCI SEQ COORD-CR/ SCI OPS COORD
- R. SPRINGER – IRIS AER/COMPUTER OPS (ALT)
- J. TRIMBLE – PRA/PWS/UVS AER
- R. WESSEN – SCI SEQ COORD-ENC

GENERAL SCIENCE DATA TEAM

CHIEF: N. TOY

DEPUTY: R. HUNGERFORD

SECRETARY: L. JACKSON

- W. ARMSTRONG – RNORT COORD
- S. BURLEIGH – VNESSA SYS SUPPORT
- (J. BYNUM) – DATA ACCOUNTABILITY
- C. BYRNE – SCI DATA ENG
- M. CIVITA – APT OPS SUPPORT
- D. GRAYSON – DATA PROG ANALYST
- (R. HUNGERFORD) – DATA CTR GRP LDR
- M. JONES – PROC ANALYST
- E. KOBERLEIN – DATA SCI OPS COORD
- L. LEE – VNESSA SYS SUPPORT
- P. LIGGETT – VNESSA SYS SUPPORT
- J. LOUIE – VNESSA
- L. NGUYEN – S/W TEST & TRAINING ENG
- T. RAY – APT OPS SUPPORT
- J. SCHWARTZ – S/W ENGR
- (E. SIMIEN) – DATA LIBRARIAN
- M. SULLIVAN – CO-OP OPS SUPPORT
- D. SWETT – DATA PROC ANALYST

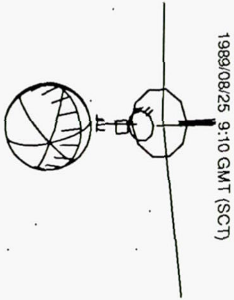
RADIO SCIENCE SUPPORT TEAM

CHIEF: D. SWEETNAM

DEPUTY: S. BORUTZKI

- S. ASMAR – GDS ENGINEER
- (S. BORUTZKI) – SCIENCE OBS. COORD
- (M. DELITSKY) – ASSISTANT SCIENCE OBS COORD
- A. DENSMORE – GDS S/W ENGINEER
- P. ESHE – DATA PROD ENGR
- D. MORABITO – OPERATIONS ENGR
- Y. H. SON – S/W ENGR

( ) = MULTIPLE APPEARANCES



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1989/08/25 9:10 GMT (SCT)

Table 15-2. Voyager Project Organization (Continued)

FLIGHT ENGINEERING OFFICE

MANAGER:	L. MILLER
DEPUTY:	K. SAVARY
STAFF ENGR:	G. HINTZ
ADMIN. ASSISTANT:	L. OSMOND

SEQUENCE TEAM

CHIEF:	M. DEUTSCH
DEPUTY:	K. WELD
SECRETARY:	L. HUGHES

- D. BLUHM – DATA OPS/SEQGEN ANAL
- C. COLEMAN – SEQ SYS ENGR
- S. DODD – SEQ INTEG ENGR
- M. FOX – DATA OPS/SEQGEN ANAL
- D. HELLER – SEQ INTEG ENGR
- S. HERMAN – CAT2 S/W ENGR
- (A. KO) – CCS/COMSIM ENGR
- (R. LEMON) – CCS/COMSIM ENGR
- S. LEVER – CCS/COMSIM ENGR
- M. MOLANDER – SCI SEQ DES
- J. MORRIS – DATA OPS/SEQGEN ANAL
- R. MURDOCK – CCS/COMSIM ANAL
- (W. NELSON) – TELECOM ENGR
- K. NGUYEN – G&C ENGR
- P. O'BRYAN – SEQ SYS ENGR
- B. ROSS – SEQ INTEG ENGR
- (E. SHIRINYAN) – G&C LEAD
- R. THOMAS – SEQ INTEG ENGR
- W. THOMPSON – G&C ENGR
- B. WAGGONER – SCI SEQ DES
- C. WEISS – DATA OPS/SEQGEN ANAL
- G. WELCH – CCS COMSIM ANAL
- B. WIER – SCI SEQ DES
- M. WONCIK – TELECOM ENGR
- R. YEN – FDS/DTR/COMSIM ENGR
- L. ZOTTARELLI – FDS/DTR/COMSIM ENGR

NAVIGATION TEAM

CHIEF:	D. GRAY
SECRETARY:	C. VOURNAS

- C. BROWN – RDC ENGR
- L. CAMPANELLI – RDC ENGR
- R. CESARONE – LEAD MVR & TRAJ ANAL
- K. FRANCIS – MNVR ANAL
- G. GOLTZ – MNS CHIEF
- L. IRIKS – TSAC ANAL
- R. JACOBSON – EPH ANAL
- K. LEE – RDC ENGR
- G. LEWIS – OD ANAL
- L. LIGHT – RDC ENGR
- S. MATOUSEK – TRAJ ANAL
- M. MEDINA – RDC ENGR
- W. OWEN – OPNAV ANAL/CONSULT
- C. POTTS – MNVR ANAL
- E. RIEDEL – LEAD OPNAV ANAL
- G. ROLDAN – RDC ENGR
- D. ROTH – OD ANAL
- J. STUVE – OPNAV ANAL
- S. SYNNOTT – OPNAV SUPV
- A. TAYLOR – LEAD OD ANAL
- R. VAUGHAN – OPNAV ANAL

SPACECRAFT TEAM

CHIEF:	H. MARDERNESS
DEPUTY:	J. HALL
SECRETARY:	S. HOFMANN
DOCUMENTARIAN:	R. ESTRADA

- R. ACHEY – PWR CE
- A. AVILA – TEMP ANAL
- R. BADIN – TEMP ANAL
- P. BARROS – FDS/DSS ANAL
- M. BELHADEF – SPCAL ANAL
- E. BLIZZARD – FDS S/W DEVEL
- B. BONZO – PROP ANAL
- C. CHILDS – DATA SYSTEMS ENGR/DSE
- F. CLOUGH – GC&P RT ANAL
- W. COOK – CCS/DSS ANAL/DSE
- R. COWLEY – PROP ANAL
- G. COX – SP ANAL
- W. CUNNINGHAM – ISS DSL/ANAL
- K. DAR – SEQ DEV SYS LEAD
- L. DAVIS – TELECOM RFS/RT ANAL
- S. deJESUS – FDS CDL ENGR
- R. ELLIS – CDL TST ENGR/FDS LEAD ENGR
- R. EVEY – RT SYS ANAL
- D. FAIR – TELECOM NRT/TRK ANAL
- K. FLYNN – TELECOM RT ANAL
- G. HANOVER – GC&P DSL
- H. HARPER – RT SYS LEAD
- N. HAYES – HGA POINTING CE
- J. HINTON – RT TELECOM ANAL
- T. HOFFMAN – FDS/CDL ENGR/DSE
- T. HOGLE – AACS FLT S/W CSE CONT PLAN
- B. JACKSON – RT SYS ANAL
- C. JACKSON – CCS FLT S/W/FPA CSE/BML DEV
- S. KANG – RT CMD SYS LEAD/QA SUP
- S. KEREGHA – SEQ DEV SYS LEAD
- (A. KO) – CCS/COMSIM ANAL
- (R. LEMON) – CCS/COMSIM ANAL
- H. LIN – AACS PERF ANAL
- R. LUDWIG – RT TELECOM ANAL
- B. MADSEN – TELECOM SUPVR & DSL
- J. MALLOY – ISS NRT ANAL
- W. MATTSON – TELECOM CE
- M. MAYO – GEN SCI DSL/ANAL
- B. McDOUGAL – RT GEN SCI ANAL
- E. MEDINA – SEQ DEV
- K. MEREDITH – ISS NRT ANAL
- D. MILLER – FDS CDL TEST ENGR
- M. MILLER – CEL SENSOR CE
- M. MINE – FDS FLT S/W CSE/SEQ DEV SYS LEAD
- A. MONCADA – PWR SUBSYSTEM ANAL
- E. NAGLE – GC&P RT ANAL
- L. NAKAMAURA – MNVR ANAL, SEQ DEV
- (W. NELSON) – TELECOM SEQ REVIEW
- R. OTAMURA – DATA SYS SPVR/DSL
- K. PATEL – AACS ANAL
- H. PHAM – GC&P RT ANAL
- C. PRESLEY – DATA SYS ENGR
- J. RHOADS – G&C SPVR, GRD S/W ANAL
- R. RICE – FDS S/W DEV
- V. RUSSELL – ISS RT ANAL
- K. SCHOENI – ISS NRT ANAL
- K. SEDWICK – G&C DOCUMENTATION
- (E. SHIRINYAN) – SEQ LEAD
- J. SIMS – G&C RT ANAL
- J. SMITH – TEMP/PROP DSL/ANAL
- R. SPRIESTERBACH – CCS ANAL
- A. STERGER – TELECOM RT ANAL
- T. TAKAHASHI – CDL ENGR
- A. TERADA – DATA SYSTEM ENGR
- N. THOMAS – FDS/DSS ANAL
- V. WAGER – SCT GRD S/W CE
- E. WAHL – MNVR ANAL
- T. WEEKS – GC&P RT LEAD, SEQ DEV
- P. YOSHIOKA – CCS S/W ENGR

( ) = MULTIPLE APPEARANCES

Table 15-2. Voyager Project Organization (Continued)

FLIGHT OPERATIONS OFFICE

MANAGER:	T. ADAMSKI
DEPUTY:	I. WEBB
ASSISTANT (ENC PREP)	A. BOUCK
ADMIN. ASSISTANT	W. NELSON
SCHEDULING:	F. MERRIMAN
SECRETARY:	D. ZEKAS

MISSION CONTROL TEAM

CHIEF: J. NASH

MISSION CONTROLLERS
- S. ANNAN
- W. BARTLETT
- B. BRYMER – (LEAD)
- J. TULLIUS
- B. NARON

SOE SUPPORT
- J. NEWMAN – ENGR
- L. DAHL – TECHNICIAN
- P. KIYAK – TECHNICIAN
- K. MARTINEZ – TECHNICIAN

OPS ENGINEERS
- M. BROWER
- D. DOODY

UNIVAC OPS
- I. ESQUIVEL – RJE COORD
- W. GRAY – PLANNING

DATA TECHS
- K. FIMBRES (LEAD)
- M. CERVANTES
- K. NARUSIEWICZ
- D. WALKER

T&T ENGINEER
- W. MOGENSEN

MCC OPERATIONS CONTROL TEAM

FOPE: C. BROWER

ASST. FOPE: E. CAMPOS

- D. ACHEY – COMPUTER SYSTEMS MAINTENANCE
- (C. AVIS) – MIPL COE
- L. JENNINGS – DATA PROCESSING OPERATIONS

DSN OPERATIONS CONTROL TEAM

NOPE: J. JONES

DEPUTY NOPE: C. FINLEY

ASST. NOPE A. KNIGHT

- J. HODDER – MISSION PLANNING/ SCHEDULING
- A. SALAZAR – OPERATIONS ENGINEERING/ ANALYSIS
- W. HERNDON – CONTROL CENTER OPERATIONS AND SUPPORT

DATA MANAGEMENT TEAM

CHIEF: M. ORR

- W. ARMSTRONG - DATA BASE ANALYST
- M. BOYKINS - PROC ANALYST
- (J. BYNUM) - DATA ACCOUNTABILITY
- D. FORBES - PROC ANALYST
- B. HILL - DATA BASE ANALYST
- E. HUNTER - DATA BASE ANALYST
- G. JOHNSON - PROC ANALYST
- J. LAXAMANA - SASDRS
- V. LEWIS - DATA BASE ANALYST
- H. PETERSEN - UNIT COORDINATOR

( ) = MULTIPLE APPEARANCES

TIME: 0 Days, 5:15:00
1989/08/25 9:15 GMT (SCT)

TO TRITON: 40314 KM

With more knowledge comes a deeper, more wonderful mystery, luring one on to penetrate deeper still.
Richard Feynman

16. COMING ATTRACTIONS

When Voyager 2 slips past Neptune to begin its interstellar mission, NASA/JPL spacecraft will have visited every known planet in the solar system except Pluto. Although these past missions have rewarded us with extraordinary glimpses of the other worlds orbiting the Sun, in many cases what we have collected is precisely that—glimpses. To understand better what these missions have shown us or hinted at, we must go back with other spacecraft.

Consider the most unforgettable moments of the Voyager Project, as it unlocked mysteries at Jupiter, Saturn, Uranus, and soon, Neptune. During the past twelve years we were astonished by erupting volcanoes on Io and complex, colorful eddies in Jupiter's atmosphere; organic compounds at Titan and the haunting beauty of the braids in Saturn's rings; and the cockeyed "prizefighter's face" geography of the Uranian moon Miranda. As gratifying as all these experiences were, they were achieved while our spacecraft were flashing by at incredible speeds. They all point to many other questions that we would like to answer by returning for another, more thorough, look.

The same is true of other planets in the solar system. Venus, for example, has been studied by more spacecraft than any other planet—eleven Soviet craft and nine from the United States. But the radar mapping instrument on our next Venus mission, Magellan, which was launched recently by the Space Shuttle on May 4, 1989, is ten times more powerful than similar mappers on any previous spacecraft. Magellan's data will allow planetary scientists to distinguish between confusingly similar categories of geological formations on Venus and get a much better idea of how our closest neighbor in the solar system evolved.

Complex revisit missions are also in the works for Jupiter and Saturn. Project Galileo—due for launch in fall 1989—will place a heavily instrumented probe into Jupiter's atmosphere and a capable spacecraft in orbit about the planet; both accomplishments will be firsts at this body. The Cassini mission to Saturn has similar goals, except the probe will be dropped into the thick atmosphere of Saturn's moon Titan, with hopes that it will reach that body's unseen surface.

Planets are not the only targets of upcoming missions at JPL. One spacecraft, Comet Rendezvous Asteroid Flyby, or CRAF, will expand on the "snapshot" data of international missions to Comet Halley in 1986 by meeting up with and traveling along with Comet Kopff for more than three years. Several NASA/JPL mission designs also include asteroid encounters for the first time, taking advantage of passes through the asteroid belt as the spacecraft speed toward their next planetary target.

Voyager 2 at Neptune and the launches of two planetary craft in 1989 provide an inspiring prelude for another long-awaited space event: launch of the Edwin P. Hubble Space Telescope, probably in early 1990. By placing this telescope in orbit above the distortions of the Earth's atmosphere, we will be able to detect objects 100 times fainter than those visible from ground-based telescopes. The Hubble telescope is a complex project that has been coordinated between three NASA centers, private contractors, and several institutions. JPL built the telescope's Wide-Field/Planetary Camera, one of its chief instruments.

Among the roster of solar system targets we shouldn't neglect is the Earth itself. Advanced satellites from the United States and other countries will be launched in the early 1990s to give us a much more comprehensive and detailed view of our planet's climate systems. JPL is preparing instruments such as the NASA Scatterometer, a device for studying ocean winds, due to be launched on a Japanese satellite. Other JPL projects include Topex, a satellite which will map circulation of the world's oceans, and one of the orbiting platforms for Eos, a major NASA Earth-observation program.

Apart from such unmanned space projects, JPL also staffs an office near Washington, D.C., supporting development of NASA's space station, Freedom. This is a manned laboratory, the components of which will begin to be put in orbit as early as the mid-1990s.

As you follow launches in the years ahead, you will notice changes in the launch vehicle used. In addition to Magellan, the next two planetary missions involving the United States (Galileo and Ulysses) will be carried into Earth orbit by the Space Shuttle. After each spacecraft is released by the Shuttle, an upper-stage motor attached to the probe fires and sends the craft off to its eventual destination. Several missions, notably Galileo to Jupiter, have undergone many launch scenarios and upper-stage configuration changes before and after the Challenger accident in 1986. Galileo in particular will now take a circuitous path to Jupiter, swinging by

the Earth twice and Venus once to pick up "gravity assist" energy to compensate for an upper-stage motor less powerful than originally planned.

After those missions on the Shuttle, we will return to expendable rockets for planetary spacecraft launches. Most of the JPL missions will use Titan IV rockets, more powerful versions of the vehicles that launched the Voyagers. The joint U.S.-French Topex/Poseidon satellite will be orbited by the European-built Ariane rocket.

The following pages summarize JPL space projects being developed or under study. At the end is a descriptive summary of mission concepts that are probably farther in the future—and that would take us literally out to the threshold of the stars.

Notice: *Information in this chapter was correct at the time of Guide publication.*

Magellan

Comparing Venus and the Earth is the story of two seemingly near-identical twins that grew up to be improbably different. Although the closest planet to Earth in size and distance from the Sun, Venus has a surface temperature of up to 480°C (900°F) and a crushing atmosphere of carbon dioxide.

Venus' atmosphere shrouds surface details from us, so orbiting spacecraft must use imaging radar to map the planet. Magellan's radar will achieve resolutions about 10 times better than that of Soviet Venera spacecraft and 100 times better than the United States' last planetary mission, Pioneer Venus, launched in 1978. The Magellan data will help scientists answer questions in diverse areas, from the mechanics of continental drift on Earth to the cause of Venus' high temperatures, and perhaps even the sequence of events that gave birth to our own planet.

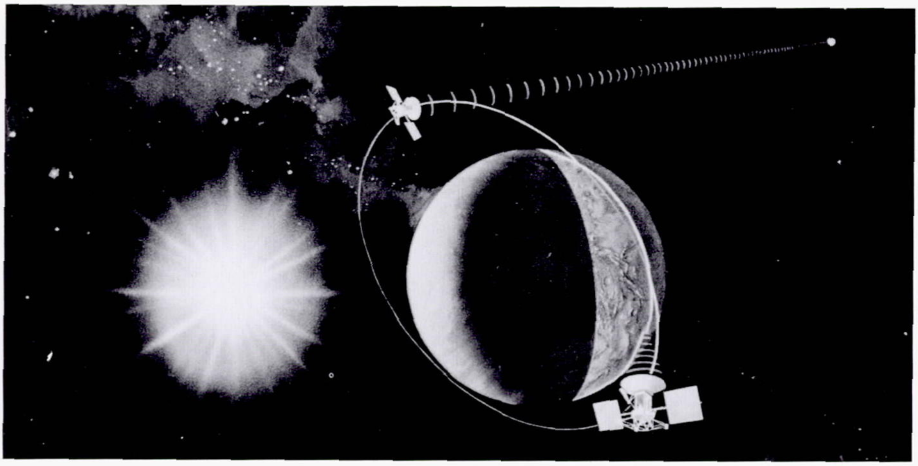
Objectives

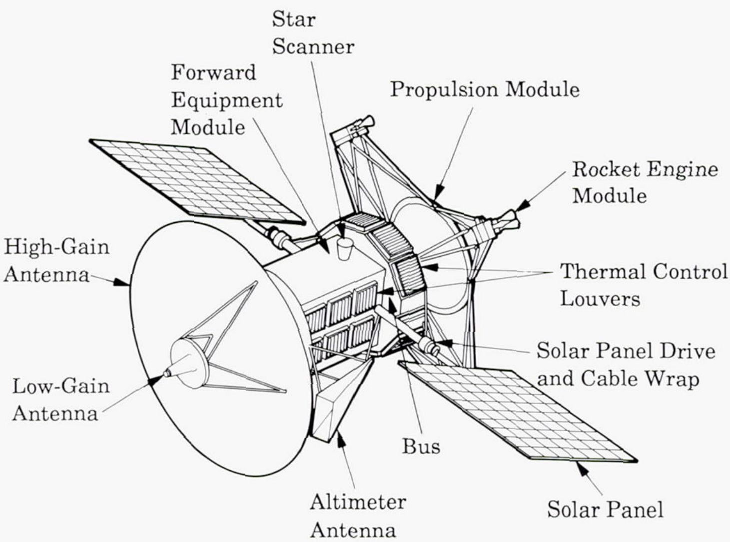
★ Infer geological history of Venus
★ Acquire global imaging and altitudes
★ Map surface features and craters
★ Search for evidence for volcanoes, plate tectonics, ancient seas and rivers
★ Study greenhouse effect
★ Map gravity field specifics
★ Compare with terrestrial planets

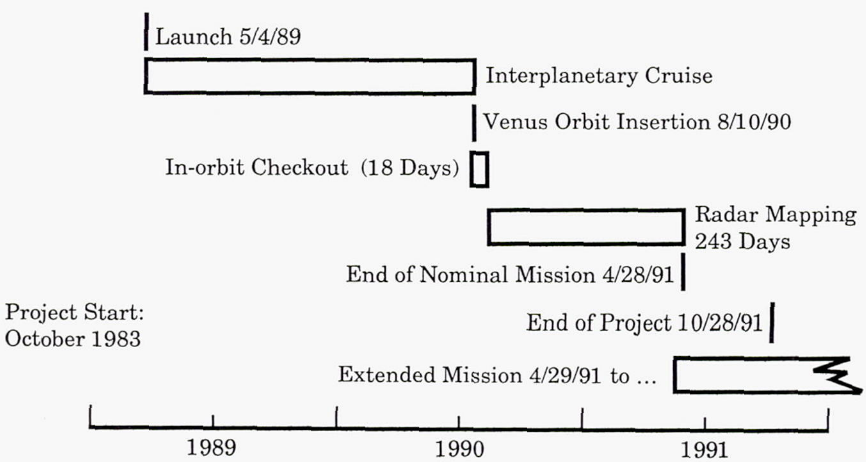
Instruments

★ Radar imager
★ Radar altimeter
★ Radiometer
★ Radio science

TO TRITON: 42624 KM




Star Scanner
Forward Equipment Module
Propulsion Module
Rocket Engine Module
High-Gain Antenna
Thermal Control Louvers
Solar Panel Drive and Cable Wrap
Low-Gain Antenna
Bus
Altimeter Antenna
Solar Panel


Launch 5/4/89
Interplanetary Cruise
Venus Orbit Insertion 8/10/90
In-orbit Checkout (18 Days)
Radar Mapping 243 Days
End of Nominal Mission 4/28/91
Project Start: October 1983
End of Project 10/28/91
Extended Mission 4/29/91 to ...
1989
1990
1991

Galileo

The environment is so complex at Jupiter, the largest planet of our solar system, that the giant and its satellites are like a miniature solar system of their own. We will be able to add many times over to what was learned from the Pioneers and Voyagers when Galileo arrives in 1995 for direct measurements of the Jovian atmosphere and an orbital mission of at least two years.

With the exception of the Vikings that landed on Mars, Galileo is the most complex planetary spacecraft ever built. The Galileo orbiter has two sections, one which slowly spins and the other which does not. In this way it combines the best aspects of previous spacecraft: experiments which measure fields and particles are on the spinning segment to cancel out interference from the spacecraft's electronics, while cameras and other instruments that need to be held steady are on the "despun" segment. Five months before reaching Jupiter, the orbiter will release an instrumented probe which will make a parachuted descent into the planet's highly active atmosphere.

On its circuitous route to Jupiter, Galileo will gain energy from two gravity assists at Earth and one at Venus, performing science observations during those encounters, including some unique observations of Earth's Moon. Along the way, Galileo will also encounter two asteroids, Gaspra and Ida, as it traverses the asteroid belt between Mars and Jupiter.

Objectives

- ★ Directly sample Jupiter's atmosphere
- ★ Conduct long-term studies of atmosphere
- ★ Conduct close-up studies of Jovian satellites
- ★ Map structure and dynamics of magnetosphere
- ★ Map thermal properties of planet

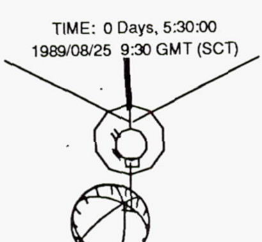
Instruments

Orbiter

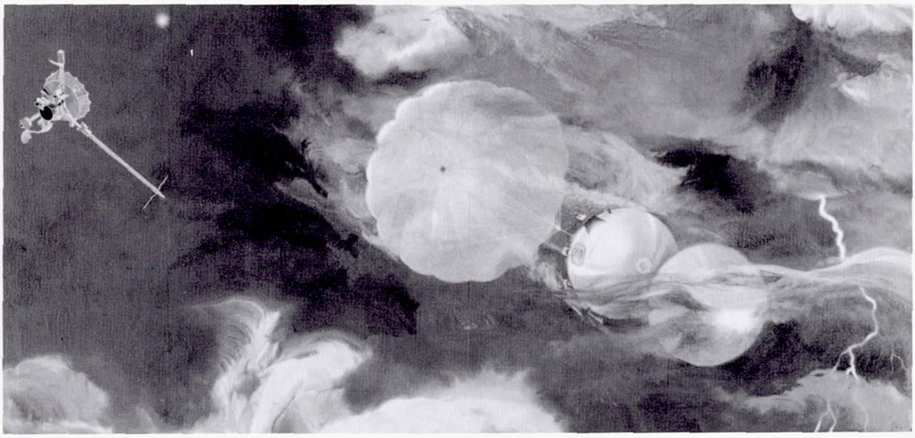
- ★ Four optical sensors
- ★ Four fields and particles detectors
- ★ Dust detector
- ★ Radio science

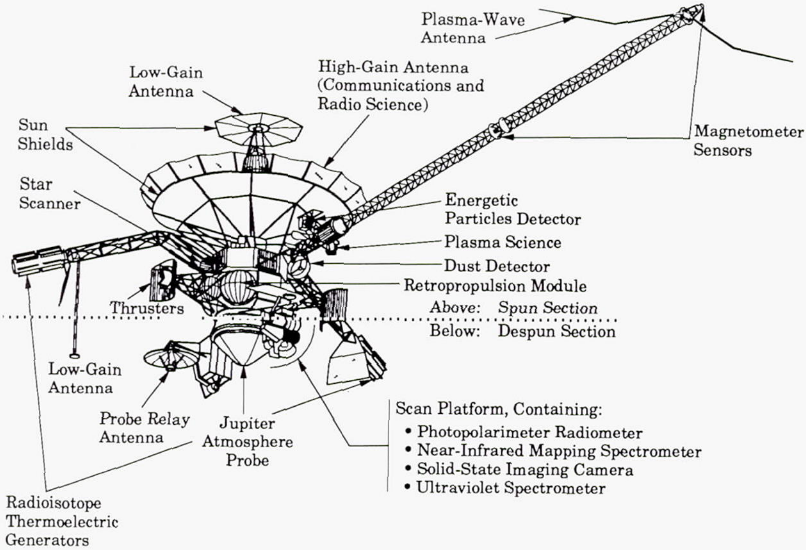
Probe

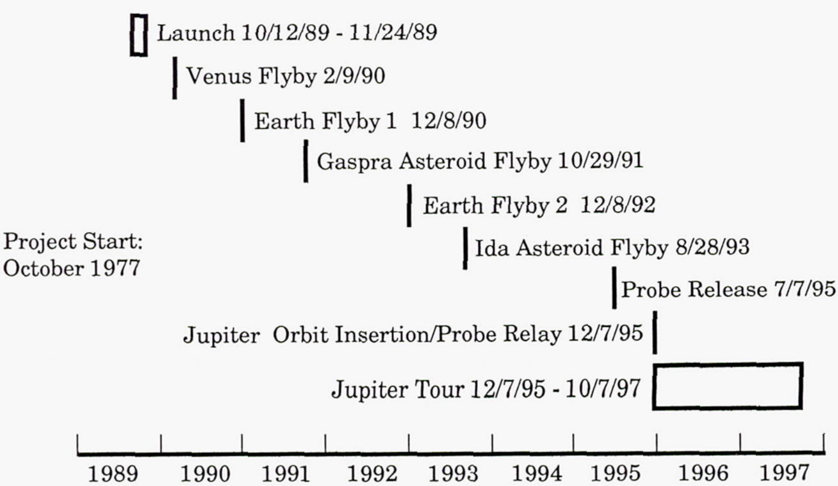
- ★ Three chemical analysis instruments
- ★ Cloud detector
- ★ Radiometer
- ★ Lightning and energetic particle detector



TO TRITON: 44748 KM







ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

Wide-Field/Planetary Camera—Hubble Space Telescope

The difference between NASA's Hubble Space Telescope and current ground-based optical telescopes can be compared to the difference between Galileo Galilei's first telescope and its predecessor, the human eye.

This orbiting observatory will detect objects 100 times fainter than those visible from Earth telescopes, with about 10 times greater spatial resolution. It will extend our reach in the cosmos from a present limit of about 2 billion light-years to roughly 15 billion light-years—allowing us to look back in time nearly to the beginning of the universe.

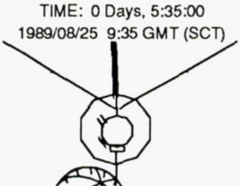
JPL's contribution to this project is the Wide-Field/Planetary Camera, one of the telescope's main science instruments. This camera can operate in two modes: "wide-field" mode views large areas of sky, allowing scientists to plot the spatial relationships of distant objects such as galaxies and quasars; the "planetary" mode views a narrower field and is designed for studying objects within the solar system.

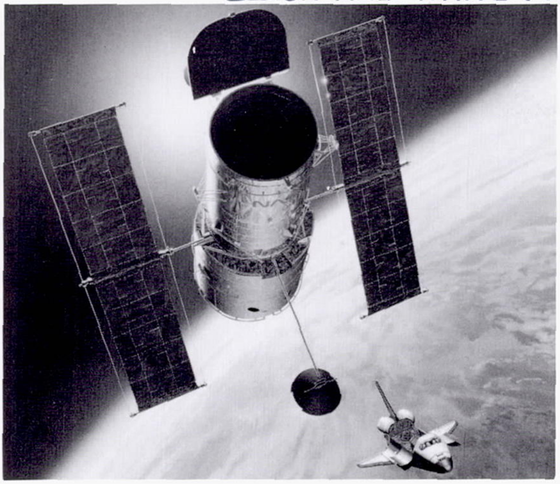
Objectives

- ★ Study cosmic evolution and distances
- ★ Image stars and galaxies
- ★ Conduct star and galaxy motion studies
- ★ Map interstellar energy distribution
- ★ Search for planets around Sun and other stars
- ★ Image planetary atmospheres and surfaces, satellites, asteroids and comets

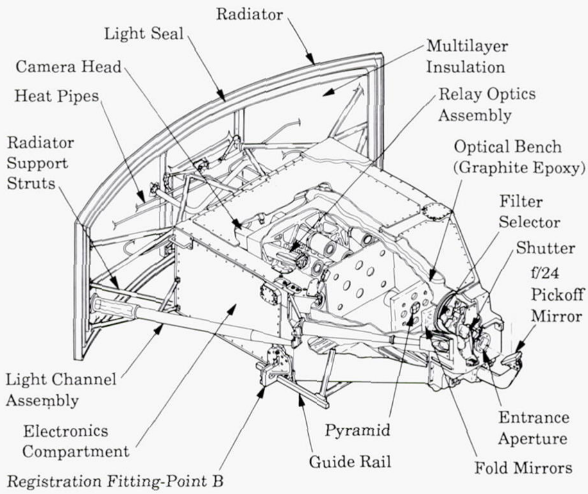
Hubble Space Telescope Instruments

- ★ Wide-Field/Planetary Camera
- ★ Faint-object spectrograph
- ★ High-resolution spectrograph
- ★ High-speed photometer
- ★ Faint-object camera
- ★ Fine-guidance sensors

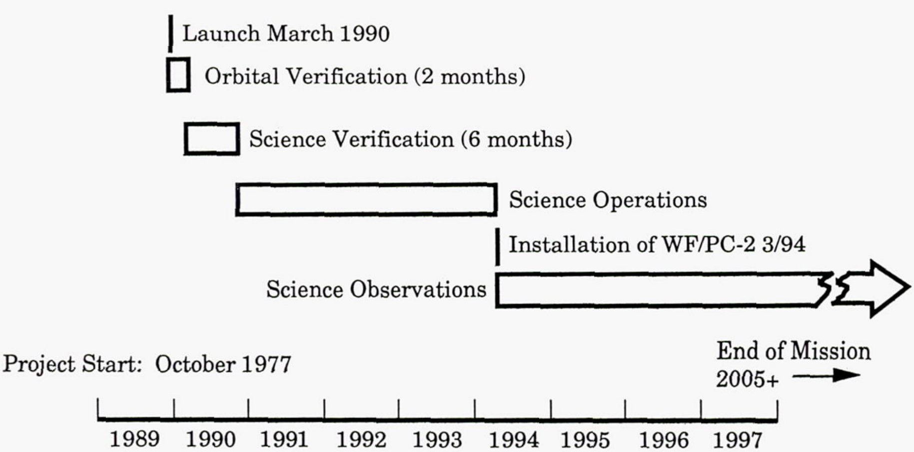




Hubble Space Telescope



Wide-Field/Planetary Camera



Ulysses

Astronomers have learned over time that the Sun, a seemingly homogenous ball of light and heat, is in fact a complex realm of its own with diverse structural, thermodynamic, and nuclear phenomena. Until now we have only been able to study the plasmas and particles streaming from the Sun from a perspective within the ecliptic—the two-dimensional plane in which the Earth and most of the planets orbit the Sun.

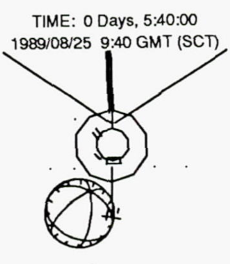
Ulysses, a joint mission between the European Space Agency (ESA) and NASA, will add a third dimension to this view by studying the Sun, solar wind and interstellar space at almost all solar latitudes. After a launch from the Space Shuttle, the ESA-developed Ulysses spacecraft will travel first to Jupiter, where the gravity of the giant planet will bend the spacecraft's path up and away from the ecliptic plane. The spacecraft will then travel back over the poles of the Sun and study it using its ESA- and NASA-supplied instruments for several years.

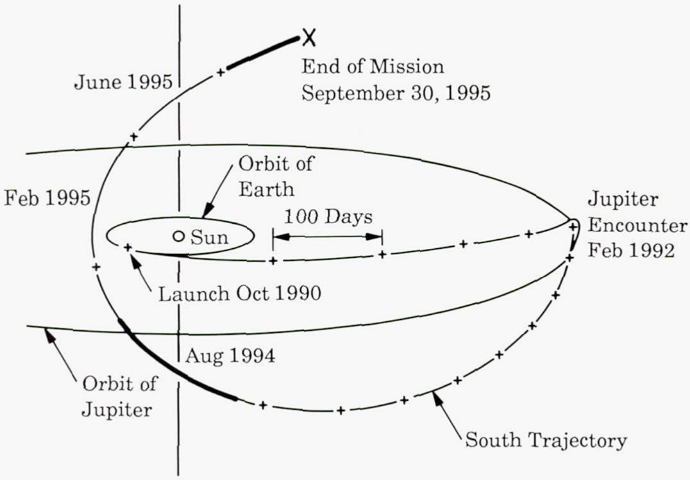
Objectives

- ★ Conduct fields and particles exploration of Sun's polar regions and regions far from ecliptic plane
- ★ Characterize inner heliosphere at all solar latitudes

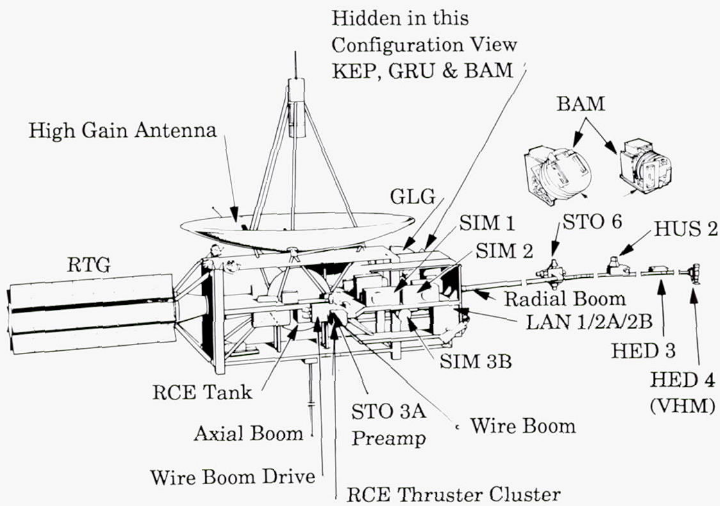
Instruments

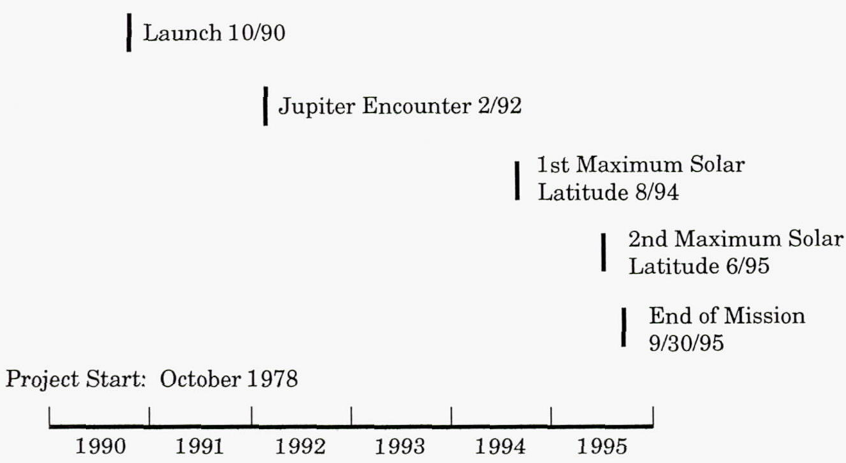
- ★ Magnetometers (HED)
- ★ Seven particle/wave/ plasma detectors
  - – Solar-wind plasma (BAM)
  - – Solar-wind ions (GLG)
  - – Low-energy ions and electrons (LAN)
  - – Energetic particles and interstellar gas (KEP)
  - – Cosmic ray/solar particles (SIM)
  - – Unified radio and plasma waves (STO)
  - – Solar x-rays/cosmic gamma-ray bursts (HUS)
- ★ Dust detector (GRU)
- ★ Radio science
  - – Coronal sounding
  - – Gravitational waves





250 Days Above 70°, Maximum Latitude 85°





Topex/Poseidon

What causes the devastation of a climate phenomenon like the El Niño currents in the Pacific? Why do continents experience droughts one year and flooding another? To help answer these questions, scientists are collaborating on an array of international experiments and studies in the 1990s to better understand interactions between the world's oceans and long-term weather trends.

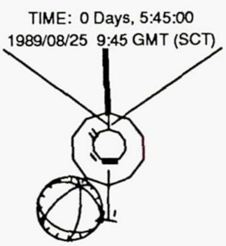
NASA's Ocean Topography Experiment, or TOPEX, and France's Poseidon mission have been combined to make highly detailed and accurate maps of the marine geoid—the shapes produced by sea levels around the world. Sea level is related to ocean currents and eddies, and by taking gravity into account researchers will also be able to calculate major features of the ocean floors. The U.S.-built spacecraft will be launched by a French Ariane rocket and carry instruments contributed by each of the two countries. Its primary mission is planned to span three years.

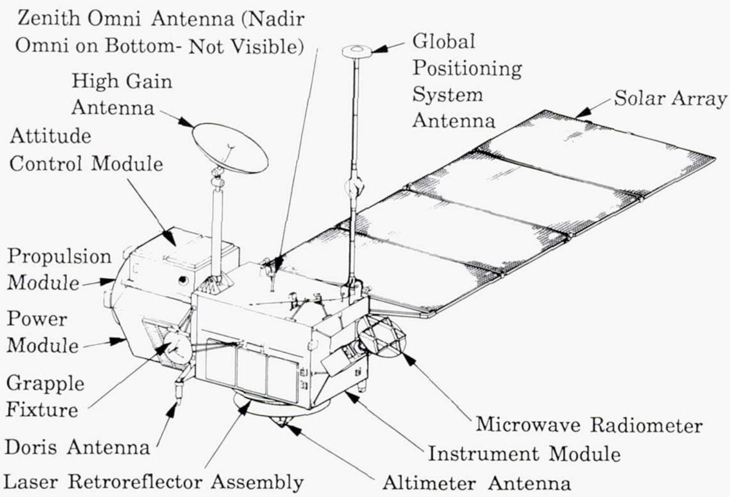
Objectives

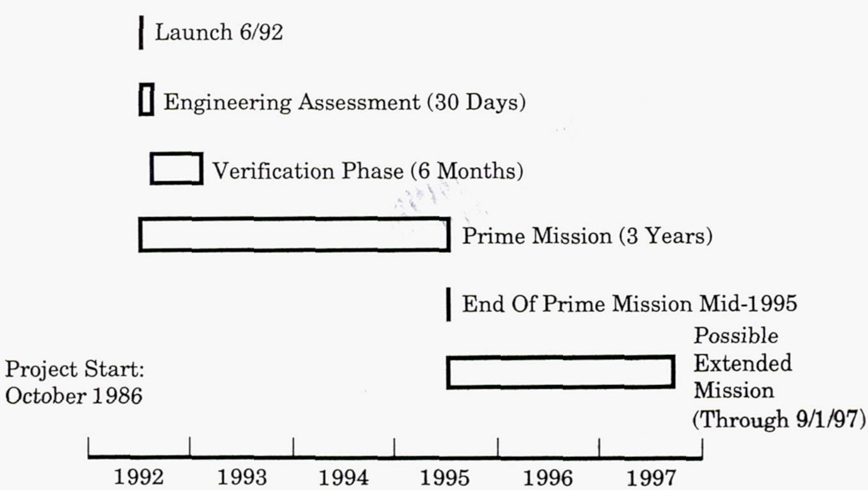
- ★ Observe ocean topography for several years, supporting global studies of:
  - Ocean circulation and variability
  - Ocean dynamics and role in climate
  - Circulation/wind interactions
  - Current/wave interactions
  - Heat, mass, nutrient and salt transport
  - Tides

Instruments

- ★ Two altimeters
- ★ Microwave radiometer
- ★ Laser retroreflector
- ★ Two positioning system receivers




Zenith Omni Antenna (Nadir Omni on Bottom- Not Visible)
Global Positioning System Antenna
High Gain Antenna
Solar Array
Attitude Control Module
Propulsion Module
Power Module
Grapple Fixture
Doris Antenna
Laser Retroreflector Assembly
Microwave Radiometer
Instrument Module
Altimeter Antenna


Launch 6/92
Engineering Assessment (30 Days)
Verification Phase (6 Months)
Prime Mission (3 Years)
End Of Prime Mission Mid-1995
Possible Extended Mission (Through 9/1/97)
Project Start: October 1986
1992
1993
1994
1995
1996
1997

Mars Observer

Much as Magellan at Venus will improve on the missions before it, Mars Observer will provide views of the red planet beyond those possible from the Viking orbiters launched in 1975. The spacecraft is the first in a series called Planetary Observer, which adapts the bus of a satellite typically used only for Earth-orbiting missions for use as a general inner solar system explorer. Mars Observer is scheduled for launch in 1992 with a Titan III rocket and Transfer Orbit Stage (TOS), a new upper stage concept.

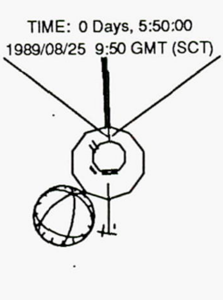
The mission's chief purpose is to study the surface, atmosphere and climate of Mars throughout a full Martian year of 687 Earth days. Imaging from an orbit lower than that of the Viking orbiters, the Mars Observer Camera will produce panoramic, high-resolution surface maps—useful for planning future lander missions. The spacecraft will also contain French-built equipment to relay data from surface-exploration balloons released by the Soviet Union's Mars '94 mission. Ten Soviet scientists are directly participating in Mars Observer studies.

Objectives

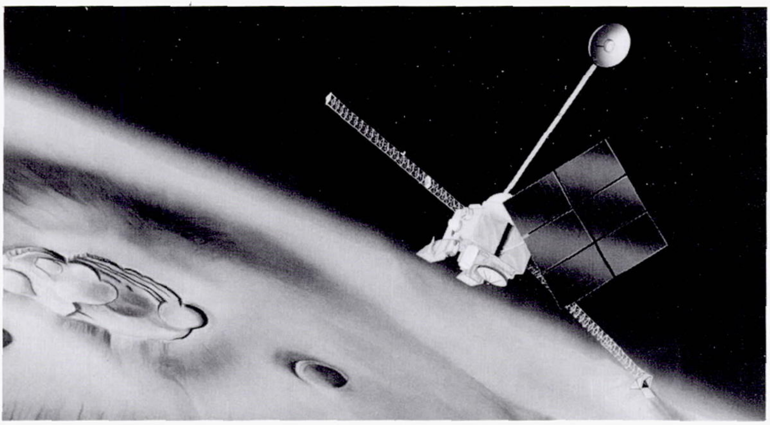
★ Conduct global studies of:
- Elemental composition of surface
- Distribution of surface minerals
- Topography
- Gravitational field
- Seasonal movement of water and dust
- Atmospheric circulation

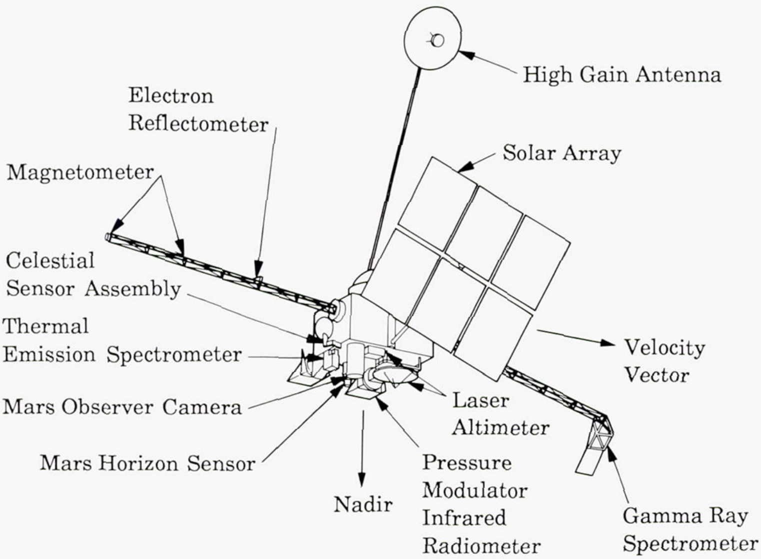
Instruments

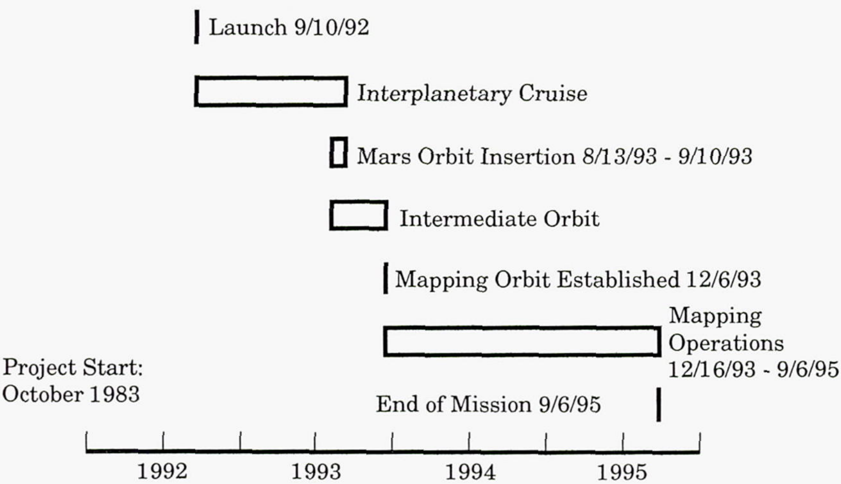
★ Gamma ray spectrometer
★ Laser altimeter
★ Wide-angle, high-resolution camera
★ Two thermal emission detectors
★ Magnetometer
★ Mars '94 balloon data relay
★ Radio science



TO TRITON: 57833 KM




High Gain Antenna
Electron
Reflectometer
Solar Array
Magnetometer
Celestial
Sensor Assembly
Thermal
Emission Spectrometer
Velocity
Vector
Mars Observer Camera
Laser
Altimeter
Mars Horizon Sensor
Pressure
Modulator
Infrared
Radiometer
Nadir
Gamma Ray
Spectrometer


Launch 9/10/92
Interplanetary Cruise
Mars Orbit Insertion 8/13/93 - 9/10/93
Intermediate Orbit
Mapping Orbit Established 12/6/93
Mapping
Operations
12/16/93 - 9/6/95
Project Start:
October 1983
End of Mission 9/6/95
1992
1993
1994
1995

Comet Rendezvous Asteroid Flyby

The more scientists have learned about comets in recent years, the more they have become intrigued. For years, it has been suspected that comets were very primitive objects from the outer solar system, essentially unchanged from the era in which the solar system formed, and that they may have originally brought water to the inner planets. Data retrieved from the international missions to Comet Halley in 1986 also suggested that comet nuclei contain organic compounds, which raises other questions about their role in the creation of life on Earth.

Comet Rendezvous Asteroid Flyby, or CRAF, will extend the Halley experience by meeting Comet Kopff near the orbit of Jupiter and traveling along with it for at least three years as the comet loops around the Sun. It will also launch a penetrator-lander which will directly sample the comet's nucleus. On the way to Kopff, CRAF will encounter the asteroid Hamburga. CRAF will be the first in a new series of outer planet exploration missions using the JPL-designed Mariner Mark II spacecraft bus.

Objectives

Comet Rendezvous

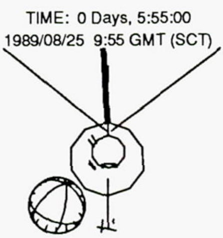
★ Characterize comet nucleus and coma
★ Study process of comet tail formation
★ Study tail dynamics and interactions with radiation and solar wind

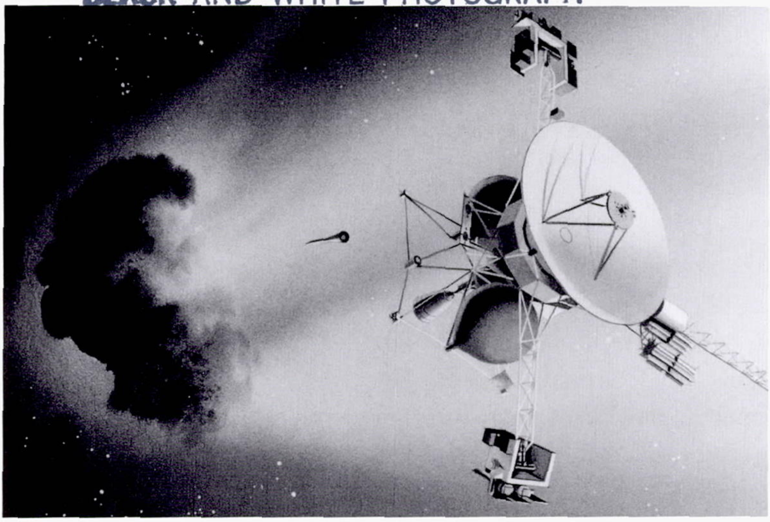
Asteroid Flyby

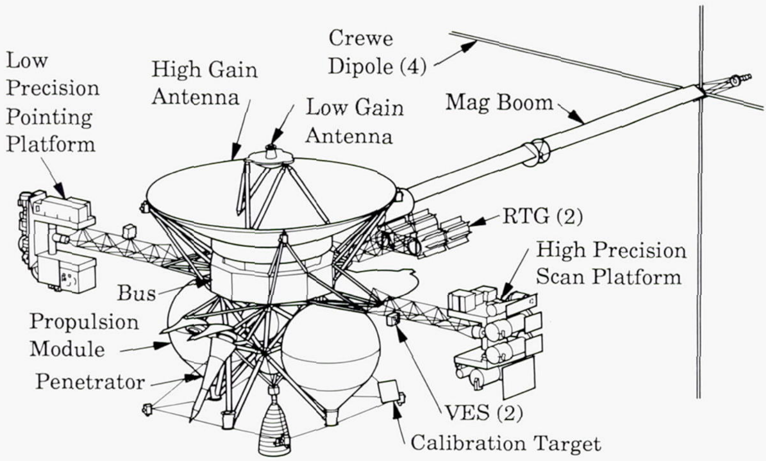
★ Characterize structure and geology
★ Determine distribution of minerals, metals, and ices
★ Measure mass, density, and nearby environment

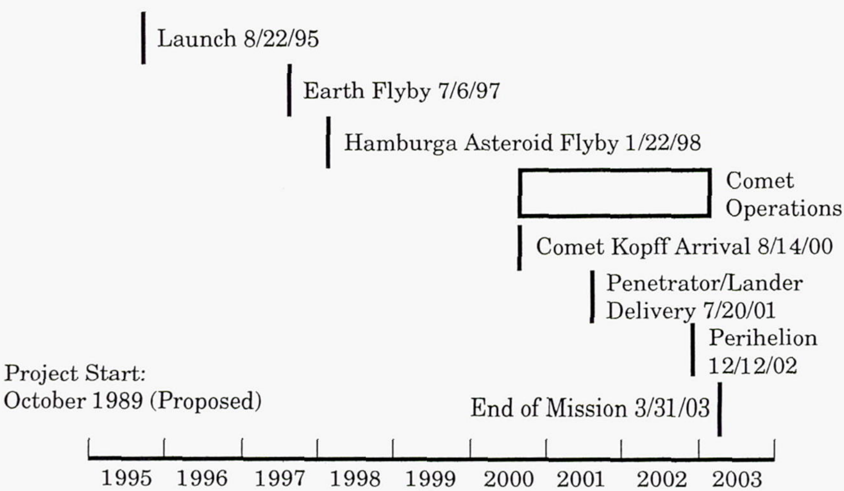
Instruments

★ Comet penetrator/lander (includes temperature probes and surface strength and composition sensors)
★ CCD narrow- and wide-angle cameras
★ Near- and far-infrared spectrometers
★ Seven particle/dust/ice/gas/plasma analyzers
★ Magnetometer
★ Radio science






Crewe
Dipole (4)
Low
Precision
Pointing
Platform
High Gain
Antenna
Low Gain
Antenna
Mag Boom
RTG (2)
High Precision
Scan Platform
Bus
Propulsion
Module
Penetrator
VES (2)
Calibration Target


Launch 8/22/95
Earth Flyby 7/6/97
Hamburga Asteroid Flyby 1/22/98
Comet
Operations
Comet Kopff Arrival 8/14/00
Penetrator/Lander
Delivery 7/20/01
Perihelion
12/12/02
Project Start:
October 1989 (Proposed)
End of Mission 3/31/03
1995 1996 1997 1998 1999 2000 2001 2002 2003

Cassini

Cassini will follow CRAF as the second mission in the new Mariner Mark II series of spacecraft to the outer solar system. Named for the Franco-Italian astronomer who discovered the gap in Saturn's rings (as well as several Saturnian moons), Cassini will return to the ringed planet for four years of orbital studies.

A probe provided by the European Space Agency and carried to Saturn by the orbiter will descend to the surface of Titan, Saturn's largest moon. Named Huygens, for the Dutch scientist who discovered Titan, the probe will study the atmosphere of the moon, which the Voyagers showed to have organic chemistry similar to simple precursors to life. If it survives the descent, the probe will continue to relay (for several minutes only) data from Titan's surface, which may be covered with puddles or even oceans of liquid ethane.

Objectives

★ Conduct detailed studies of Saturn's atmosphere, rings, and magnetosphere

★ Conduct close-up studies of Saturnian satellites

★ Characterize Titan's atmosphere and surface

Instruments

Orbiter

★ Six optical sensors

★ Nine fields and particles detectors

★ Titan radar mapper

★ Radio science

Probe

★ Five atmospheric characterization instruments

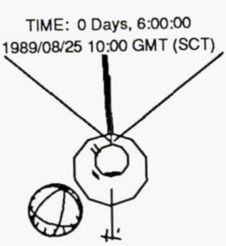
★ Descent imager and radiometer

★ Radar altimeter

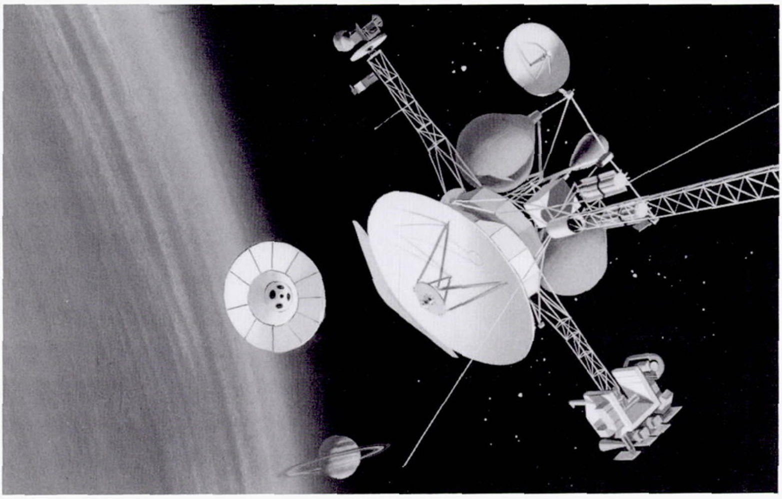
★ Lightning and radio emission detector

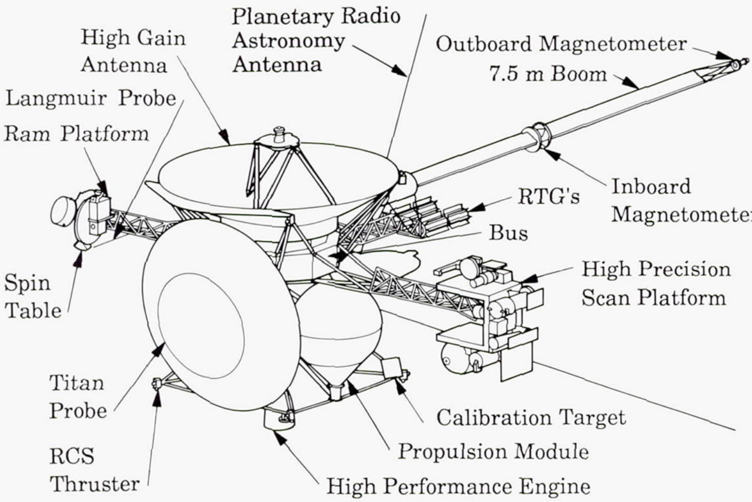
★ Surface science package

Note: Above instruments from model (not approved) payload.



TO TRITON: 66152 KM





Launch 4/8/96

Maja Asteroid Flyby 3/29/97

Earth Flyby 6/8/98

Jupiter Flyby 2/6/00

Saturn Arrival 12/6/02

Satellite Plane
Tour 12/6/02 - 12/31/06

Huygens Probe Descent
to Titan 3/17/03

Project Start:
October 1989 (Proposed)

End of
Mission
12/31/06

1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006

Earth Observing System

The most ambitious study of our own planet will begin in late 1997 when NASA launches the first orbiting platform in the Earth Observing System, or Eos. Combining instruments that study atmosphere, oceans, land surfaces and the solid Earth, the two initial Eos platforms built by NASA's Goddard Space Flight Center (Eos-A and Eos-B) may be joined by two spacecraft from Europe and one from Japan.

Both of the U.S. platforms will be launched into polar orbits on Titan IV rockets and are scheduled to be replaced every five years. The goal of the program is to study the entire Earth as a system, from the innermost core to the outermost magnetic field boundary.

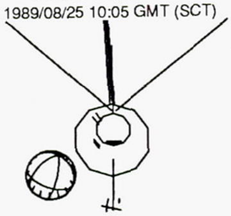
Although the definition of the Eos program is still changing, JPL will continue to be involved in the general coordination of the scientific objectives and the development of the instruments.

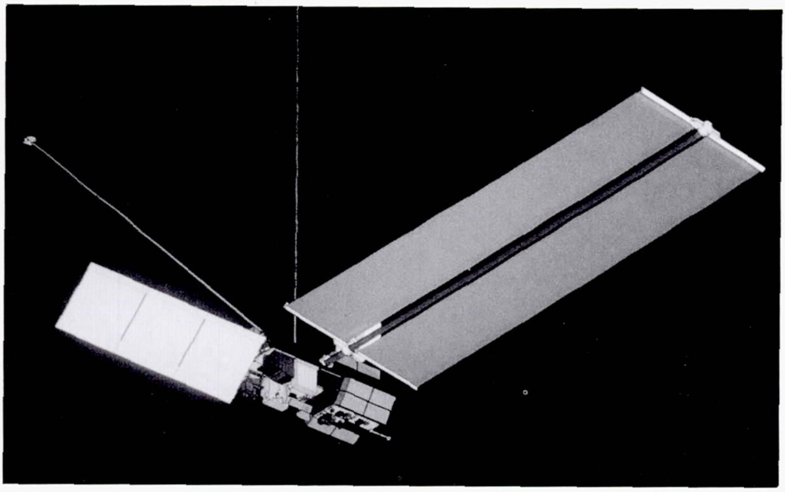
Objectives

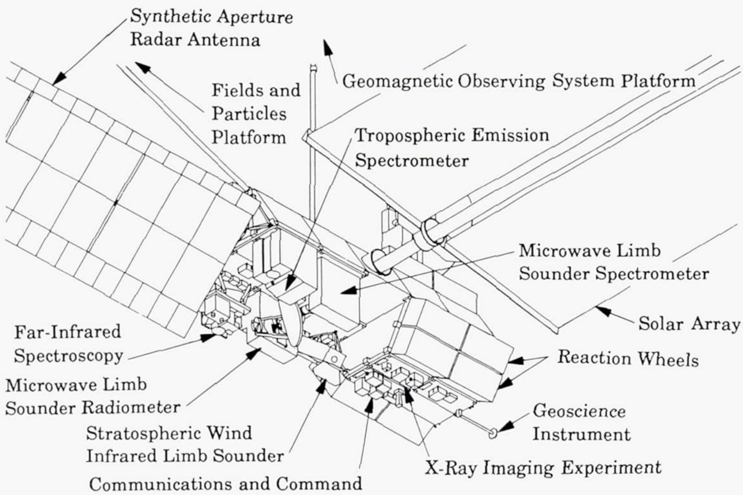
- ★ Study Earth as a unified system, including:
  - Rainfall
  - Oceanography
  - Atmospheric composition and processes
  - Pollution and fires
  - Land-based phenomena
  - Distribution of ice and snow
  - Solar and magnetospheric variations
- ★ Conduct high-resolution mapping of surface

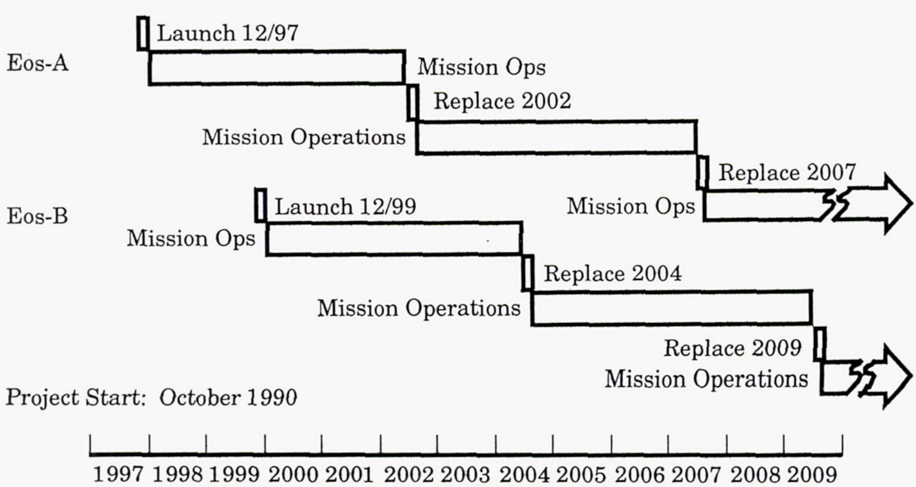
Instruments (JPL provided)

- ★ Synthetic aperture radar
- ★ Five atmospheric characterization instruments
- ★ Three geoscience packages
- ★ Space environment monitor






Synthetic Aperture Radar Antenna
Fields and Particles Platform
Geomagnetic Observing System Platform
Tropospheric Emission Spectrometer
Microwave Limb Sounder Spectrometer
Solar Array
Reaction Wheels
Geoscience Instrument
X-Ray Imaging Experiment
Communications and Command
Stratospheric Wind Infrared Limb Sounder
Microwave Limb Sounder Radiometer
Far-Infrared Spectroscopy


Eos-A
Launch 12/97
Mission Ops
Replace 2002
Mission Operations
Replace 2007
Mission Ops
Eos-B
Launch 12/99
Mission Ops
Replace 2004
Mission Operations
Replace 2009
Mission Operations
Project Start: October 1990
1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009

Mars Rover Sample Return

As the most ambitious exploration of Mars short of landing humans there, Mars Rover Sample Return would send a rover robot to roam across the planet, collecting soil and rock samples for return to Earth.

The rover itself—prototypes of which have been under development at JPL for several years—will be equipped with stereo computer vision and sophisticated artificial-intelligence expert-system software to allow it to make many immediate maneuvering and science decisions itself. This is necessary because the round-trip speed-of-light time of up to 40 minutes from Earth to Mars precludes a ground controller commanding every rover action. The rover would be able to travel up to 100 km (62 mi) per year as it conducts its studies of the Martian surface.

In one reference scenario, four rockets would separately launch an imaging orbiter, a communications orbiter, the rover lander, and a sample return vehicle. The returned samples would be retrieved in Earth orbit by the Space Shuttle.

JPL is specifically studying the rover and sample return mission concepts. The four-mission concept shown in the schedule may be integrated into a much larger multinational effort involving many countries.

Objectives

- ★ Directly study Martian surface
- ★ Return samples of surface and atmosphere to Earth for analysis
- ★ Determine history, environment, and climate
- ★ Demonstrate readiness for human exploration of Mars

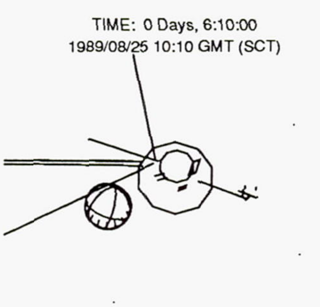
Instruments

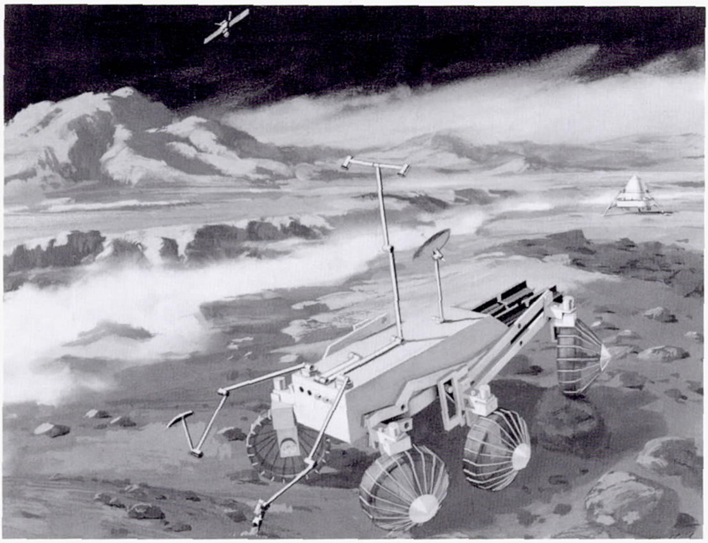
Rover

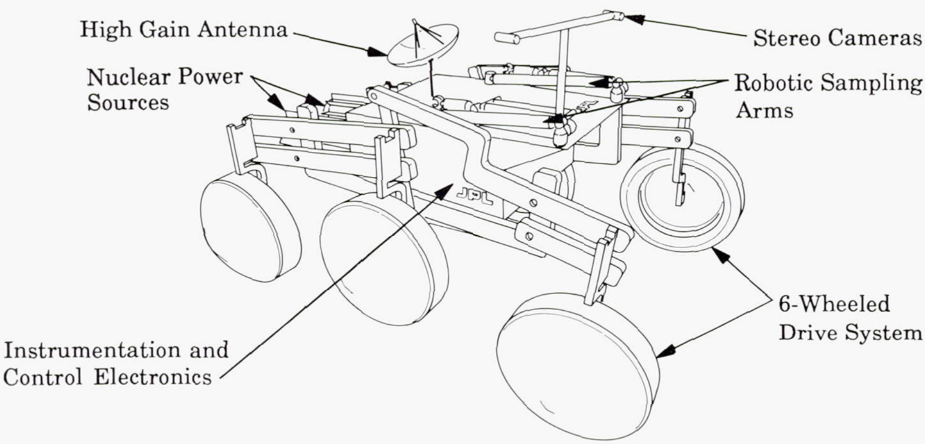
- ★ Stereo cameras
- ★ Multispectral imagers
- ★ Four geoscience packages

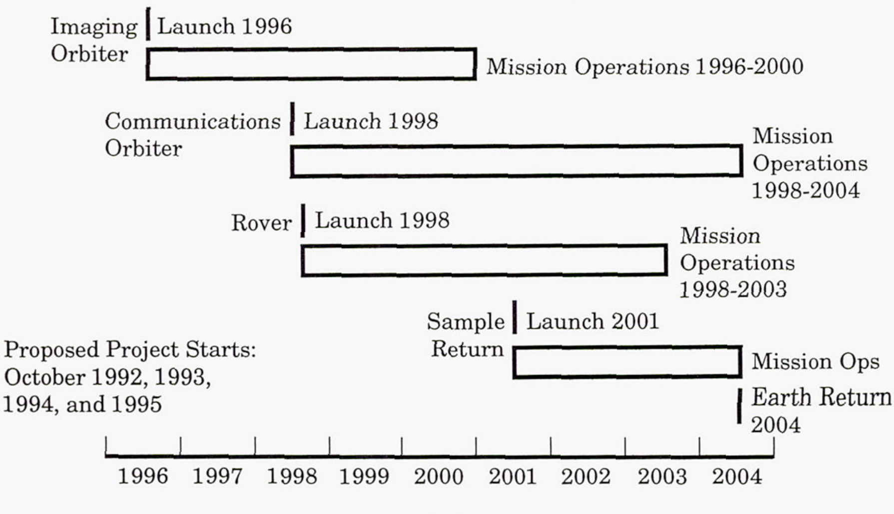
Imaging Orbiter

- ★ High-resolution camera (down to 1-m resolution)






High Gain Antenna
Stereo Cameras
Nuclear Power Sources
Robotic Sampling Arms
Instrumentation and Control Electronics
6-Wheeled Drive System


Imaging Orbiter
Launch 1996
Mission Operations 1996-2000
Communications Orbiter
Launch 1998
Mission Operations 1998-2004
Rover
Launch 1998
Mission Operations 1998-2003
Sample Return
Launch 2001
Mission Ops
Earth Return 2004
Proposed Project Starts: October 1992, 1993, 1994, and 1995
1996
1997
1998
1999
2000
2001
2002
2003
2004

Mission Concepts

In addition to the current space projects with organized teams, many other mission concepts are under study at JPL. Some may be proposed as missions for the 1990s, while others are possible projects for the early 21st century. Examples include:

Circumstellar Imaging Telescope:

This telescope, attached to the U.S. Space Station Freedom, would search for protoplanetary material or even very large planets around nearby stars.

Large Deployable Reflector:

This would be an array of telescopic mirrors in Earth orbit to study cosmology, galactic evolution, the interstellar medium, star formation, and protostars.

Lunar Geoscience Observer:

A follow-on mission in the Planetary Observer series, this craft would be placed into polar orbit around the Moon to measure its elemental and mineralogical composition and gravity, and assess potential resources for a manned lunar base.

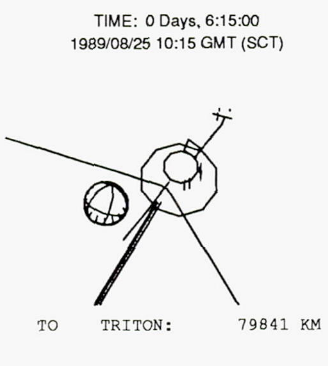
Comet Nucleus Sample Return:

This follow-on mission in the Mariner Mark II series would acquire and return to Earth samples of a comet nucleus core, a sealed sample with volatile components, and a surface sample.

Mercury Orbiter:

Specially engineered for a hot environment, this craft would study Mercury's magnetic origin, magnetosphere, atmosphere, ionosphere, surface, fields and particles, and solar physics.

Thousand Astronomical Unit (TAU):



Equipped with a nuclear reactor, ion propulsion, and light-wave communications system, this advanced spacecraft would be sent on a 50-year journey 1,000 astronomical units (about 100 billion miles) into space. Initially TAU would be directed for an encounter with Pluto, followed by passage through the heliopause and perhaps the inner Oort Cloud, the hypothetical region where comets originate. This vehicle would be instrumented to investigate low-energy cosmic rays, low-frequency radio waves, interstellar gases, gravity waves, and other deep-space phenomena. One of its chief uses would be to perform high-precision astrometry—measurements of the distances between stars.

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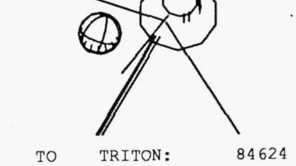

TO TRITON: 84624 KM

Every great advance in science has issued from a new audacity of imagination.

John Dewey

17. MEANWHILE, BACK ON EARTH . . .

The Voyager mission has been in the making for over two decades, including the pre-Project work. Much has happened here on Earth during that time. Some of the Flight Team members have spent their entire working careers on this project. Many have started and raised their families in synch with mission events (how many people do you know who relate "Johnny was born between second Jupiter and first Saturn"?) We thought it might be fun to look back on the last 17 years on Earth, while the Voyager Project was in the making and making history: Although our list has a decidedly space-oriented bias, you might want to pencil in your own significant events. (Many thanks to Alexander Hellemans and Bryan Bunch, authors of *The Timetables of Science*, copyright 1988.)

1972

Congress approves *Mariner Jupiter/Saturn '77 (MJS'77)* mission

ERTS-1 (first *Landsat*) is launched

First computerized axial tomography (CAT scan) is introduced

Soviet *Venera 8* soft lands on Venus

Pioneer 10 is launched to Jupiter

Apollo 17, last manned mission to the Moon, returns 110 kg of lunar material

1973

Science payload for *MJS'77* is confirmed.

NASA and Atomic Energy Commission sign agreement on nuclear power sources (RTGs) for *MJS'77*

Mariner 10 is launched to Venus and Mercury

U.K. joins European Common Market

Pioneer 10, first spacecraft to encounter Jupiter, experiences Jupiter's severe radiation environment

A calf is produced from a frozen embryo

Three Skylab missions collect 171 days of data

First nuclear magnetic resonance (NMR) scanner is introduced

1974

Impact of Jupiter's radiation environment is studied

Standard trajectories are selected

Seventy percent of spacecraft procurement contracts are finalized

Mariner 10 becomes first spacecraft to encounter Mercury

U.S. President Richard M. Nixon resigns as a result of Watergate break-in cover-up

Pioneer 11 encounters Jupiter and is redirected toward Saturn

Skeleton of "Lucy," 3-million year-old *Australopithecus afarensis* species, is found

Scientists warn that chlorofluorocarbons may be destroying Earth's protective ozone layer

Hewlett Packard introduces first programmable pocket calculator

1975

Final Spacecraft System Design Review

Mission Operations System functional requirements written

Deliveries of key parts impacted by nation-wide recession

Last American troops are withdrawn from Vietnam

Very Long Baseline Interferometry is implemented

Soviet *Veneras 9* and *10* return first pictures of surface of Venus

Apollo-Soyuz Test Project is launched

First liquid-crystal displays for digital clocks and calculators are marketed

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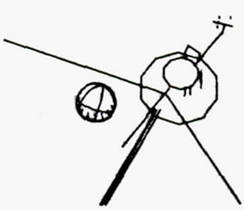

TO TRITON: 89490 KM

1976

Proof Test Model spacecraft assembled and begins environmental tests

Assembly of flight spacecraft begins

Tentative flight path selected

U.S. celebrates 200th anniversary of Declaration of Independence

Vikings 1 and *2* land on Mars

Scientists in an airborne observatory discover rings around Uranus

First commercial company aimed at genetic engineering is established

Supersonic *Concorde* begins regularly scheduled passenger service

1977

Mariner Jupiter/Saturn 1977 is renamed *Voyager*

Voyagers 1 and *2* are launched

Voyager 1 returns first spacecraft photo of Earth and Moon

U.S. space shuttle *Enterprise* completes first approach and landing test

The King of Rock 'n' Roll, Elvis Presley, dies

Two men in New York become earliest victims of Acquired Immune Deficiency Syndome (AIDS)

Last recorded case of smallpox in the wild is found in Somalia

Balloon angioplasty is invented to unclog diseased arteries

Apple II computer is introduced

1978

Voyager 2's main radio receiver fails; tracking loop capacitor fails in backup receiver

Backup mission load designed to perform Jupiter encounter in event of receiver loss

Planning begins for Jupiter observations

Charon, only known satellite of Pluto, is discovered

Seasat performs imaging radar studies of ocean's surface from space

Pioneer Venus probes are launched

First "test-tube baby" is born

1979

As *Voyager 1* swings through the Jovian system, it discovers eight active volcanoes on Io and a thin dust ring around Jupiter

Four months later, *Voyager 2* is able to observe six of Io's volcanoes still erupting

Planning begins for Saturn observations

Egypt and Israel sign accord at Camp David to end their 30-year war

Human-powered airplane *Gossamer Albatross* crosses the English channel

Nuclear reactor at Three Mile Island, NJ undergoes a partial meltdown

Pioneer 11 becomes first spacecraft to encounter Saturn

1980

Voyager 1 swings through the Saturn system, reveals complexity of Saturn's rings and sees a haze-enshrouded Titan

Voyager 1 begins its trip out of the solar system, rising above the ecliptic plane

Voyager Project recommends that *Voyager 2* be sent on to Uranus

Very Large Array begins operation in Socorro, NM

Mt. St. Helens erupts

Successful production of human interferon in bacteria is announced

Machine is developed to break up kidney stones with sound waves

Scientists postulate giant body impacted Earth and contributed to extinction of dinosaurs

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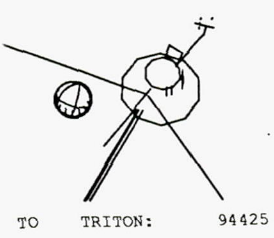

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1981

Voyager 2 swings through Saturn's system and heads for Uranus

Scan platform on *Voyager 2* sticks 102 minutes after closest approach to Saturn

Chinese scientists successfully clone a fish

Black-footed ferrets, thought extinct, are found in Wyoming

Genetic code for hepatitis B surface antigen is found

Solar One, world's largest solar-power station, is completed near Barstow, CA

IBM personal computer, using DOS, is introduced

First U.S. space shuttle, *Columbia*, completes first mission

1982

Tasks are defined to compress image data, to use FDS processors in tandem, and to use Reed-Solomon encoding

Deep Space Network upgrades two 26-m antennas to 34-m

Mary Rose, a 16th-century warship, is raised from Portsmouth, England harbor

Soviet *Venera 13* and *14* soft land on Venus

Single atom of element 109 is created

El Chicon volcano erupts in Mexico, sending dust and gases into stratosphere

First Jarvik-7 artificial heart is implanted

Compact disc players are introduced

1983

Ground testing of scan platform flight spare actuators continues

Implementation of new flight software begins

Detailed planning for Uranus begins

Infrared Astronomical Satellite (IRAS) discovers evidence of planet formation around stars outside our solar system

Immunosuppressant cyclosporine is approved for use in U.S. for organ transplants

1984

Campaign to reduce image smear begins

Work continues to devise strategy for use of ailing scan platform on *Voyager 2*

Preliminary planning begins for Neptune encounter

Soviet researchers drill to a depth of 12 km and reach Earth's lower crust

Los Angeles hosts the XXIIIrd Olympiad

Apple Computer introduces the Macintosh

Genetic fingerprinting technique is discovered

First successful surgery is performed on a fetus before birth

1985

Implementation of new flight software is completed

North polar region is selected for aimpoint at Neptune

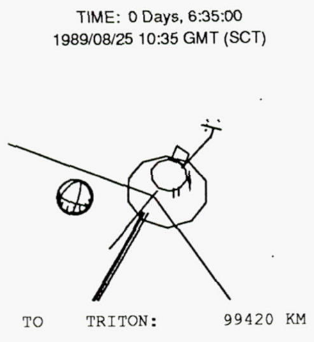
Work begins on array of Canberra antennas with Parkes Radio Observatory

Volcano Nevada del Ruiz erupts in Columbia, killing 25,000 people

British Antarctic Survey detects spring-time hole in ozone layer over Antarctica

Lasers are used to clean clogged arteries

Soviet *Vega 1* and *2* drop landers on Venus enroute to Halley's Comet



1986

Voyager 2 becomes the first spacecraft to swing by Uranus, discovering ten new moons, two new rings, and an unusual magnetic field

Deep Space Network begins upgrades including expansion of 64-m antennas to 70-m

Neptune aimpoint reconfirmed

Detailed planning begins for Neptune encounter

Voyager aircraft circles the globe in nine days without refueling

U.S. space shuttle *Challenger* explodes, killing 7 astronauts

International armada of spacecraft encounter Halley's Comet

Chernobyl nuclear reactor explodes near Kiev, U.S.S.R

Periodically inhabited Soviet space station *Mir* is launched

1987

Voyager 2 "observes" Supernova 1987A

Deep Space Network completes 34-m high efficiency antenna at Madrid

Work begins to gain additional radio science coverage with Usuda Observatory, Japan

Nodding image motion compensation is tested

Last wild California condor is trapped and placed in zoo for breeding

IBM introduces Personal System/2 computers

Supernova 1987A is observed

Yuri V. Romanenko sets new record for days in space, 326 days

Last dusky seaside sparrow dies in captivity

U.S. New York Stock Exchange drops 508 points (more than 22 percent) in one day

1988

New array of Goldstone with Very Large Array is tested

Voyager 2 continues intensive stellar UV astronomy

FDS dual processor program tested

Voyager 2 returns first color images of Neptune

Scientists directly observe the atmosphere of Pluto

First U.S. patent is issued for a vertebrate product of genetic engineering (a white mouse)

Apple introduces Macintosh II

Computer parallel processing speeds solutions by a factor of 1000

Human-powered airplane *Daedalus 88* sets new distance and time records

First Soviet space shuttle is launched unmanned and recovered

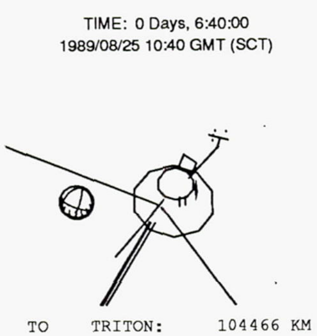
U.S. resumes space shuttle launches

1989

Manueverless image motion compensation tested

Voyager 2 will become first spacecraft to swing through Neptune's system, hoping to learn more about Neptune's atmosphere, Triton, and purported ring arcs

Voyager 2 will begin its trip out of the solar system, below the ecliptic plane



Scientists discover disturbed chemistry related to chlorofluorocarbons in stratosphere over Earth's high northern latitudes

Pluto reaches its closest point to the Sun in its 284-year orbit

Scientists claim to have demonstrated table-top, sustained, net-energy-releasing nuclear fusion

Supertanker spills millions of gallons of oil into Alaska's Prince William Sound

Trans-Pacific communications cable begins operation

U.S. *Magellan* spacecraft is launched to Venus

Speaker of the House resigns

U.S. *Galileo* spacecraft is scheduled for launch to Jupiter

Stars scribble in our eyes the frosty sagas,
the gleaming cantos of unvanquished space.

Hart Crane

18. STILL CURIOUS?

We've tried in this Guide to pass along the excitement, wonder, and challenges of the Voyager missions, but still keep the explanations fairly simple. We hope we've whet your appetite to learn more. Much more has been written about Voyager, both in the popular press and in the scientific literature. We present here a brief list of further reading, if you so desire, for your spare time. Some of you may enjoy just browsing through one of the popular books, looking at nifty pictures, whenever a few idle minutes are available. Others of you may want to dive in and dig for the nitty-gritty details of the engineering and science of the mission. Whatever your choice, enjoy!

Books on Voyager:

Cooper, Henry S. F. *Imaging Saturn: The Voyager Flights to Saturn*. Owl Books, H. Holt & Co., 1983.

Davis, Joel. *Flyby, the Interplanetary Odyssey of Voyager 2*. New York: Atheneum, 1987.

Morrison, David C. and Jane Samz. *Voyage to Jupiter*. NASA SP-439. Washington, D.C: National Aeronautics and Space Administration, 1980.

Morrison, David C. *Voyagers to Saturn*. NASA SP-451. Washington, D.C.: National Aeronautics and Space Administration, 1982.

Poynter, Margaret and Arthur L. Lane. *Voyager: The Story of a Space Mission*. New York: Atheneum Childrens Books, Macmillan, 1981.

Sagan, Carl, and F. D. Drake, Ann Druyan, Timothy Ferris, Jon Lomberg, and Linda Salzman Sagan. *Murmurs of Earth, the Voyager Interstellar Record*. New York: Random House, 1978.

Washburn, Mark. *Distant Encounters*. Washington, D.C.: Harcourt, Brace, Jovanovich, 1983.

Note: Listings here are for information only and do not necessarily imply endorsement.

Books Pertaining to Neptune:

Burgess, Eric. *Uranus and Neptune. The Distant Giants.* Columbia University Press, 1988.

Grosser, Morton. *The Discovery of Neptune.* Cambridge: Harvard University Press, 1962.

General Books on the Solar System:

Beatty, J. Kelly, Brian O'Leary, and Andrew Chaikin, eds. *The New Solar System.* Cambridge: Cambridge University Press and Sky Publishing Corporation, 1981.

Frazier, Kendrick and The Editors of Time-Life Books. *Solar System.* Planet Earth series. Alexandria, VA: Time-Life Books, Inc., 1985.

French, Bevan M., and Stephen P. Maran, eds. *A Meeting with the Universe.* NASA EP-177. Washington, D.C.: National Aeronautics and Space Administration, 1981.

Gallant, Roy A. *National Geographic Picture Atlas of Our Universe.* Washington, D.C.: National Geographic Society, 1980.

Hoyt, William Graves. *Planets X and Pluto.* Tucson: University of Arizona Press, 1980.

Littman, Mark. *Planets Beyond, Discovering the Outer Solar System.* Wiley Science Editions. New York: John Wiley & Sons, Inc., 1988.

Smoluchowski, Roman. *The Solar System.* Scientific American Library. New York: Scientific American Books, 1983.

The Editors of Time-Life Books. *The Far Planets.* Voyage Through the Universe series. Alexandria, VA: Time-Life Books,Inc., 1989.

Trefil, James S. *Space Time Infinity.* New York: Pantheon Books and Washington, D.C.: Smithsonian Books, 1985.

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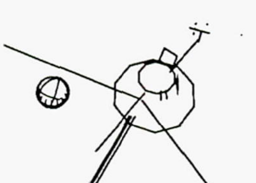

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Magazine Articles:

Popular Articles:

Articles on Voyager often appear in popular magazines such as *Astronomy*, *Discover*, *Mercury*, *National Geographic*, *New Frontier*, *Odyssey*, *Omni*, *Science News*, *Sky and Telescope*, and *The Planetary Report*. Some specific articles of interest are listed below.

Voyager and Planets:

Gore, Rick, "Voyager Views Jupiter's Dazzling Realm." *National Geographic*, January, 1980.

Gore, Rick, "Saturn, Riddles of the Rings." *National Geographic*, July 1981.

Gore, Rick, "Between Fire and Ice, The Planets." *National Geographic*, January 1985.

Gore, Rick, "Uranus, Visit to a Dark Planet." *National Geographic*, August 1986.

Laeser, Richard P., William I. McLaughlin, and Donna M. Wolff, "Engineering Voyager 2's Encounter with Uranus." *Scientific American*, November 1986.

Wiley, John P., Jr., "A spacecraft named Voyager has shown us the moons and rings of Uranus—and just how well a machine can perform." *Smithsonian*, September 1986.

Wilkinson, Stephan, "Space Geniuses Wanted: Apply JPL." *Air & Space / Smithsonian*, December 1986/January 1987.

Neptune Encounter:

Beatty, Kelly. "Voyage to a Far Moon." *Omni*, December 1988.

Berry, Richard. "Voyager's first glimpse of Neptune: a year before it encounters Neptune, Voyager 2 took its first tantalizing images of Neptune and its moon Triton." *Astronomy*, October 1988.

Berry, Richard. "Triton." *Astronomy*, February 1989.

Chiles, James R. "To the Stars!" *Reader's Digest*, December 1988.

Eberhart, Jonathan. "Planetary perks: scientific fringe-benefits of Voyager 2's trip to Neptune." *Science News*, September 10, 1988.

Eberhart, Jonathan. "High expectations for Voyager 2 at Neptune." *Science News,* November 12, 1988.

Kohlhase, Charles. "On Course for Neptune." *Astronomy*, November 1986.

Kohlhase, Charles. "Aiming for Neptune." *Astronomy*, November 1987.

Lemonick, Michael. "Neptune's Baffling Clouds." *Science Digest*, January 1985.

Littman, Mark. "The Triumphant Grand Tour of Voyager 2." *Astronomy*, December 1988.

Miner, Ellis D. "On to Neptune." *The Planetary Report*, November/December 1986.

O'Meara, Stephen J. "Neptune Through the Eyepiece." *Sky and Telescope*, May 1989.

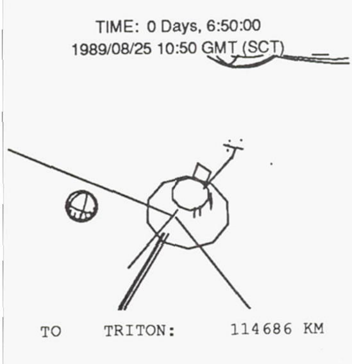
Sohus, Anita, and Ellis Miner. "The Voyager Mission to Neptune." *Mercury* (magazine of the Astronomical Society of the Pacific), September/October 1988.

Stevenson, David J. "Looking Ahead to Neptune." *Sky and Telescope*, May 1989.

Thorpe, Andrew M. "Enigmatic Triton and Nereid." *Sky and Telescope*, May 1989.

<u>Scientific Articles:</u>

Voyager science results are published in professional magazines such as *Geophysical Research Letters*, *Icarus*, *Journal of Geophysical Research*, *Nature*, *Science*, *Scientific American*, and *Space Science Reviews*, as well as in the proceedings of conferences of professional societies such as the American Astronautical Society (AAS), the American Geophysical Union (AGU), and the American Institute of Aeronautics and Astronautics (AIAA). Specific articles of interest are listed below.



Instrument and Investigation summaries:

Space Science Reviews 21, (no. 2, November 1977 and no. 3, December 1977)

Official results of the first analyses of the Voyager encounter data are traditionally published in *Science*, the magazine of the American Association for the Advancement of Science:

Science 204 (June 1, 1979): pp. 913-924 and 945-1008 (Voyager 1 at Jupiter)
Science 206 (November 23, 1979): pp. 925-996 (Voyager 2 at Jupiter)
Science 212 (April 10, 1981): pp. 159-243 (Voyager 1 at Saturn)
Science 215 (January 29, 1982): pp. 459 and 499-594 (Voyager 2 at Saturn)
Science 233 (July 4, 1986): pp. 1-132 (Voyager 2 at Uranus)

Bergstrahl, Jay, ed. "Uranus and Neptune," NASA Conference Publication 2330. Washington, D.C.: NASA, 1984.

Hubbard, W. B. "1981N1: A Neptune arc? (or new satellite)." *Science* 231 (14 March 1986): 1276.

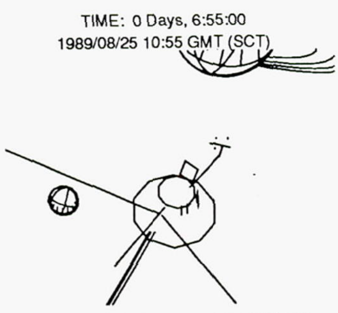
Hunten, Donald M. and David Morrison, eds. "The Saturn System," NASA Conference Publication 2068. Washington, D.C.: NASA, 1978.

"Voyager Missions to Jupiter." reprinted from *Journal of Geophysical Research* 86 (September 30, 1981, no. A10).

General Interest:

Brown, Robert Hamilton, and Dale P. Cruikshank. "The Moons of Uranus, Neptune, and Pluto." *Scientific American* 253 (July 1985): 38.

Drake, Stillman, and Charles E. Kowal. "Galileo's sighting of Neptune." *Scientific American* 243 (December 1980): 74.


TIME: 0 Days, 6:55:00
1989/08/25 10:55 GMT (SCT)
TO TRITON: 119849 KM

Here lyeth muche rychnesse in lytell space.

John Heywood

19. ALPHABET SOUP

An acronym is a handy type of shorthand, a word formed from the first letters of the words that make up a lengthy name or phrase. Some acronyms have attained the status of becoming "real" words; for example, radar (radio detection and ranging) or snafu (situation normal, all fouled up). Although used by some of the great Medieval Jewish scholars to shorten their names (e.g., Rashi for Rabbi Shelomo ben Yitzhak, 1040-1105), most acronyms were coined during and after World War II. In fact, acronyms were introduced in the February 1943 issue of *American Notes and Queries*.

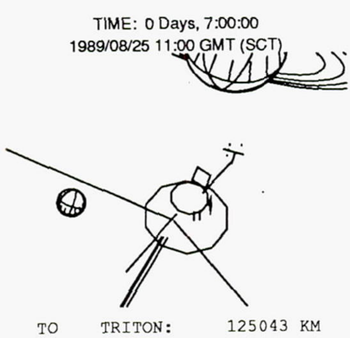
The origin of the word is Greek (*akros* [for top] plus *onyma* [for name]), but did you know that "acronym" is also an acronym? Some clever souls just had to invent a suitable phrase to give it acronym status. If you like the sophisticated, then try Algorithm for Character Reconstruction of Names Yielding Mnemonics. If you want to be a bit more honest about it, then try A Contrived Reduction of Names Yielding Mnemonics.

The very best acronyms become real words that have a meaning closely related to the acronym's own special significance. A Voyager classic is SAMPLER, standing for Science and Mission Profile Leaving Earth Region, a flight software sequence developed (but never executed as intended) to test and "sample" certain spacecraft and science capabilities shortly after launch.

On the more humorous side, Gentry Lee, formerly Project Engineer for the *Galileo* project, once remarked that a project is ready to launch when the depth of its acronyms has reached a certain level.

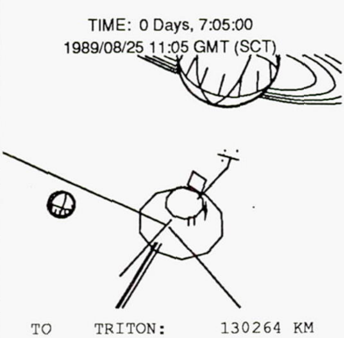
Virtually every walk of life develops its own set of acronyms. To the uninitiated, our conversations sometimes sound like alphabet soup, but acronyms can sure save time and typing! Sometimes, those of us who have been in this business for a long time still chuckle when we hear an acronym-rich dialog such as, "Our NET RFAs aren't due to low SNR at the DSN or VLA, but TBD problems may exist in the PLS EDRs, so the SOC will recheck the DACS for data gaps from CCS load B825." The secret decoding guide follows:

A	Voyager 1 reference
AACS	Attitude and Articulation Control Subsystem
AAI	All Axes Inertial
AD	anno Domini
AIAA	American Institute of Aeronautics and Astronautics
AM	Amplitude Modulation
ASFULL	PRA investigation of Neptune's magnetosphere
AU	Astronomical Unit (approx. 150 million km or 93 million mi)
Az	Azimuth
B	Voyager 2 reference
BML	Backup Mission Load
bps	bits per second
C/A	Closest Approach
C^3	Command, Communications, and Control
cc	cubic centimeter
CCS	Computer Command Subsystem
CCSL	Computer Command Subsystem Load
CDSCC	Canberra Deep Space Communications Complex (Australia)
CDT	Capability Demonstration Test
CDU	Command Detector Unit
cm	centimeter
CM	Command Moratorium
CMC	Complex Monitor Control
CMD	Command
CR	Cosmic Rays
CRS	Cosmic Ray Subsystem
CRSMVR	Cruise Manuever
CSIRO	Commonwealth Scientific and Industrial Research Organization (Australia)
CST	Canopus Star Tracker



d	day
DACS	Data Capture and Staging
deg	degree
DRS	Data Records Subsystem
DSCC	Deep Space Communications Complex
DSN	Deep Space Network (NASA)
DSS	Data Storage Subsystem, Deep Space Station
DTR	Digital Tape Recorder
EDR	Experiment Data Record
El	Elevation
ENC-REL	Encounter-Relative (time)
ERT	Earth-Received Time (occasionally, encounter-relative time
EUV	Extreme Ultraviolet
EUVE	Extreme Ultraviolet Explorer
F&P	Fields and Particles
FDS	Flight Data Subsystem
FE	Far Encounter Phase
FM	Frequency Modulation
FOO	Flight Operations Office
FOV	Field of View
FPA	Fault Protection Algorithm
FSO	Flight Science Office
FSTEP	LECP observation to detect rapid variations in Neptune's radiation field
ft	foot
FUV	Far Ultraviolet
GCF	Ground Communications Facility
GDS	Ground Data System
GDSCC	Goldstone Deep Space Communications Complex (California)
GHz	GigaHertz (one billion cycles per second)
gm	gram
GMT	Greenwich Mean Time
GS&E	General Science and Engineering
GSFC	Goddard Space Flight Center

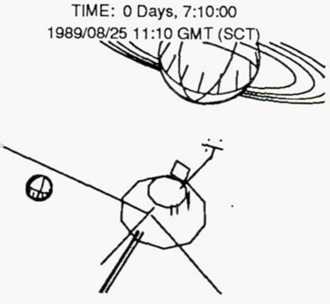
H	Hydrogen
h or hr	hour
He	Helium
HGA	High Gain Antenna
ICE	International Comet Explorer
IDC	Image data compression
IMC	Image Motion Compensation
INTA	National Institute for Aerospace Techniques (Spain)
IPM	Interplanetary Medium
IR	Infrared
IRIS	Infrared Interferometer Spectrometer and Radiometer Subsystem
ISAS	Institute of Astronautical Science (Japan)
ISM	Interstellar Medium
ISS	Imaging Science Subsystem
IUE	International Ultraviolet Explorer
JPL	Jet Propulsion Laboratory
kbps	kilo (1000) bits per second
kg	kilogram
km	kilometer
LAN	Local Area Network
lb	pound
LECP	Low Energy Charged Particles Subsystem
LEMPA	Low Energy Magnetospheric Particle Analyzer (in LECP)
LEPT	Low Energy Particle Telescope (LECP)
LETS	Low Energy Telescope System (CRS)
LEU	Late Ephemeris Update
LMC	Link Monitor Control
LSU	Late Stored Update



m	meter (also, minute)
MAG	Magnetometer Subsystem
MAGROLL	Spacecraft roll maneuver
MCCC	Mission Control and Computing Center
MCT	Mission Control Team

MHz	MegaHertz (one million cycles per second)
mi	mile
MIMC	Maneuverless Image Motion Compensation
MIPS	Multimission Image Processing Subsystem
MJS77	Mariner Jupiter/Saturn 1977
mm	millimeter
mph	miles per hour
MPO	Mission Planning Office
NA	Narrow Angle (imaging)
NASA	National Aeronautics and Space Administration
NASCOM	NASA Communications Network
NAV	Navigation Team
NE	Near Encounter Phase
NEC	Near Encounter Contingency
NET	Near Encounter Test
NIMC	Nodding Image Motion Compensation
NMB	Neptune Movable Block
NRAO	National Radio Astronomy Observatory
OAO	Orbiting Astronomical Observatory
OB	Observatory Phase
OCC	Occultation
OPNAV	Optical Navigation
ORT	Operational Readiness Test (radio science)
OWLT	One-Way Light Time
PDT	Pacific Daylight Time
PE	Post-Encounter Phase
PEO	Public Education Office (JPL)
PIO	Public Information Office (JPL)
PLS	Plasma Subsystem
POT	Potentiometer
PPS	Photopolarimeter Subsystem
PPVPHOT	Photometric observations of Neptune's atmosphere
PRA	Planetary Radio Astronomy Subsystem
PWS	Plasma Wave Subsystem

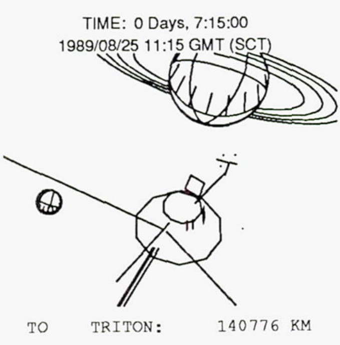
R-axis	The **R-S-T** axes refer to an orthogonal targeting coordinate system, where **S** points in the same direction as the target-relative approach hyperbolic excess velocity, **T** is parallel to the ecliptic plane, and **R** is "down"
rads	100 ergs per gram of irradiated material
RFA	Request for Action
RFS	Radio Frequency Subsystem
RODAN	Radio Occultation Data Analysis
RPDISK	IRIS observation of Nepune's disk
rpm	revolutions per minute
RPOCCPT	IRIS observation of radio science occultation point in Neptune's atmosphere
RS	Reed-Solomon; Radio Science
RSS	Radio Science Subsystem
RTG	Radioisotope Thermoelectric Generator
RTMAPIN	IRIS map of lit side of Triton
RTMAPOUT	IRIS map of dark side of Triton
S/C 31	Voyager 1 reference
S/C 32	Voyager 2 reference
SC	Scan Converter
SCET	Spacecraft Event Time
SCT	Spacecraft Team (sometimes, Spacecraft Time)
SDT	Science Data Team
sec, s	second
SEDR	Supplementary Experiment Data Record
SEQ	Sequence Team
SIS	Science Investigation Support Team
SNR	Signal-to-Noise Ratio
SOC	Science Operations Coordinator
SPC	Signal Processing Center
SSG	Science Steering Group
SWG	Science Working Group



T-axis	Refer to **R**-axis
TBD	To Be Determined
TC	Thermal Cycle
TCM	Trajectory Correction Maneuver
TET	Electron Telescope (CRS)

TMB	Triton Movable Block
TMT	Torque Margin Test
TTS	Test and Telemetry Subsystem
TV	Television
U/L	Uplink
UPCORONA	UVS observations of Neptune's corona
UPDKPOL	UVS observations of Neptune's dark pole
USO	Ultra Stable Oscillator
UTCRDRFT	UVS observation of co-rotating plasma near Triton
UTGLOW	UVS observation of airglow emissions from Triton's atmosphere
UTHOCC	UVS observation of Triton's outer atmosphere during occultation
UTPLASMA	UVS observation of co-rotating plasma near Triton
UV	Ultraviolet
UVS	Ultraviolet Spectrometer Subsystem
VCR	Video Cassette Recorder
VGR	Voyager
VIM	Voyager Interstellar Mission
VISA	Voyager Imaging Support Activity
VLA	Very Large Array
VMB	Vernier Movable Block
VNBEST	Highest resolution picture of Nereid
VNESSA	Voyager Neptune Encounter Science Support Activity
VRARCMOV1	Narrow-angle images of possible ring arcs
VRDETECT	Narrow-angle mosaics to search for possible ring arcs
VRHIPHAS	Images of possible ring arcs as sunlight is scattered through them
VRMOS1, 2	Narrow-angle images to observe possible ring arcs or shepherding satellites
VRRET1	Retargettable images of a possible newly discovered ring-arc (acronym subsequently changed to VRRETINX)
VRRETINX	See VRRET1; x = 0, 1, 2, 3 for specific application of VRRET1
VRXING2	Imaging observations during outbound ring plane crossing
VTCOLOR	Highest resolution color images of Triton
VTERM	Highest resolution images of Triton

VTLON	Periodic imaging of Triton as it orbits Neptune
VTMAP	Images to map Triton's surface
WA	Wide Angle (imaging)
WPOLE	PWS observations of plasma wave signals near Neptune's north pole
WS	Work Station
WSFULL	PWS observations of plasma wave signals in Neptune's inner magnetosphere
WSHORT05	5-second PWS observations of plasma wave signals in Neptune's inner magnetosphere
WSHORT10	10-second PWS observations of plasma wave signals in Neptune's inner magnetosphere
WWII	World War II
XROCC	Radio science observations of rings during occultation
XPOCC	Radio science observations of Neptune's atmosphere during occultations
XSGRAV	Radio science observations of gravity fields of Neptune and Triton
XTOCC	Radio science observations of Triton's atmosphere during occultation



Something hidden. Go and find it. Go and look behind the ranges. Something lost behind the ranges. Lost and waiting for you. Go!

Rudyard Kipling

20. INDEX

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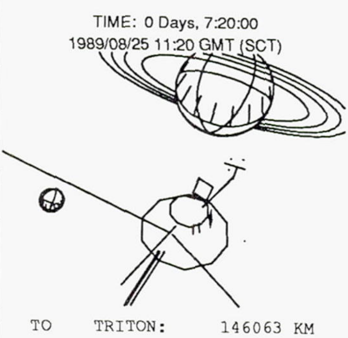

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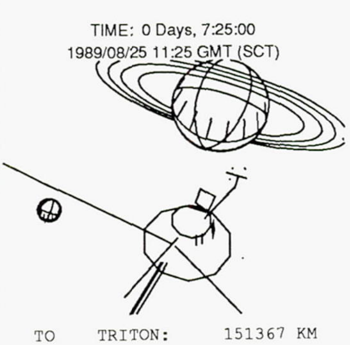

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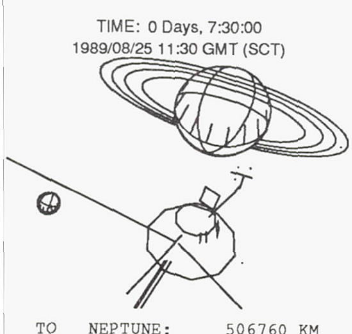

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Not fare well,
But fare forward, voyagers.
T. S. Eliot

21. MANY THANKS

The time has come to say thanks. But where do we begin? Over 3000 different people have contributed to the Voyager success, at one time or another, over the past nearly two decades. In fact, the number is even larger if we thank all of the science and news writers, and other media people as well, who thought enough of the Voyager story to share it with their reading and viewing audiences. As shown in Figure 3-4, several hundred folks are even helping out for the Neptune encounter, many of whom are named in Table 15-2.

So, in terms of specific name credits, we'll have to limit ourselves in this chapter to saying thanks to those who prepared the Guide. Originally the brainchild of Charley Kohlhase, a shorter version of the Guide was first issued for the Uranus Encounter. Because of its popularity, a decision was made to produce an expanded Guide for the Neptune encounter, the final planetary flyby for the epic Grand Tour mission. Within this Neptune Guide most of the raw writing and principal contributions for the various chapters were done by Jim Gerschultz, Robert Frampton, Charley Kohlhase, William Kosmann, Bob Neilson, Frank O'Donnell, Rex Ridenoure, Kate Robinett, and Anita Sohus.

But writers alone do not a Guide make. It must be typed, reviewed, edited, and "laid out" for the printers. In these categories, special thanks are in order for Judith McGavin and Becky Harvey (for typing and moral support), Anita Sohus and Jeanne Collins (for coordinating), to Robin Dumas (for design, layout, and production), and Roy Halton, Lee Scot and Bruce Stout (for their graphics support), and Phil Gwinn (cartoons).

Oh . . . the reviewers? Those having provided more than a handful of comments include Terry Adamski, Norm Haynes, Charley Kohlhase, Bob Mac Millin, Ellis Miner, Rex Ridenoure, and Edward Stone.

There you have it. Once again, thanks to everyone who contributed to the Voyager success. To those who first conceived of the multiplanet Grand Tour opportunity; to those who convinced the Congress to fund such a long mission; to the Congress for seeing the wisdom in providing the needed resources; to those who designed the mission, spacecraft, and science; to those who improved the facilities at Earth Base as the Voyagers journeyed farther and farther from Earth; to the Flight Team who kept the Voyagers on course, developed the flight sequences, and carefully gathered the returning scientific data; to the many scientists who interpreted the exciting discoveries; to the media who publicized the results; and, finally, to all those loyal space fans who have cheered the Voyagers along the way as they leave the outer planets and head for the stars: Many thanks!

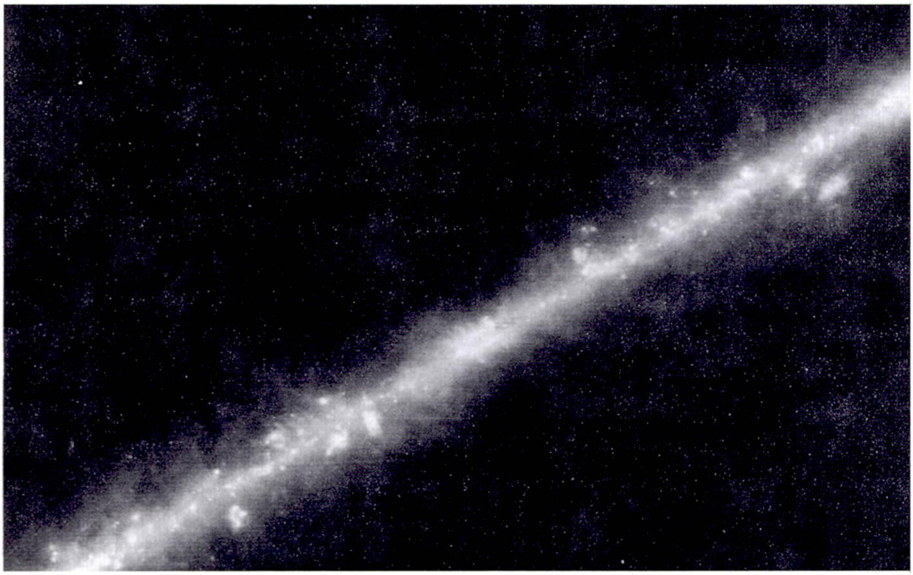


Figure 21-1. With its Grand Tour accomplished, Voyager 2 will join its companions Voyager 1, Pioneer 10, and Pioneer 11 on an escape from our home star, the Sun. For thousands and thousands of years hence, each craft will traverse unabated through the vast expanse of space between local stars, orbiting around the core of our home galaxy, the Milky Way, shown here in an edge-on view compiled from months of Infrared Astronomical Satellite (IRAS) data.

As Galileo could never have guessed how his discoveries would benefit mankind, neither can we fathom what impact the Voyager discoveries will have during the coming centuries. Our satisfaction comes from knowing that we were given a rare opportunity, and that we seized it.

Dave Field
from the video Jupiter the Giant, Saturn the Gem
Phil Neuhauser, Manager, JPL Public Education Office

HIP POCKET

Handy Facts
Voyager 2 Observations near Neptune

Voyager's Past

VOYAGER MISSION SUMMARY

Two one-ton spacecraft were launched from Earth in 1977 to explore Jupiter and Saturn. Voyager 1 encountered both planets, using Jupiter's gravity to go on to Saturn, and was flung by Saturn's gravity up out of the ecliptic plane in 1980. Voyager 2 followed Voyager 1 to Jupiter and Saturn, and then went on to Uranus and Neptune, using the gravity of each previous planet to go on to the next one. This outer planets Grand Tour requires a planetary alignment that repeats only once every 176 years.

Highlights

Jupiter
- Turbulent colorful atmosphere
- Narrow dusty ring
- 9 active volcanoes on Io
- Surfaces of all 4 Galilean moons
- Lightning and aurora

Saturn
- 1000 mph winds
- Elaborate, varied structure of rings
- Surfaces of all major moons except Titan
- Titan atmosphere 90% nitrogen

Uranus
- Tilted, off-center magnetic field
- *Rich terrain variety on Miranda*
- Surfaces of all 5 major moons
- 10 new moons and 2 new rings

Problems

Voyager 1
- PPS failed (3/5/79)
- PLS failed (11/23/80)
- FDS memory B failed (10/6/81)
- X-band TWT failed (10/29/87)

Voyager 2
- Telemetry system degraded (9/23/77)
- PPS, MAG, IRIS, CRS, PRA, PWS, LECP degraded (various)
- Command receiver #1 failed (4/5/78)
- Command receiver #2 degraded (4/6/78)
- *NA camera sensitivity degraded (8/1/81)*
- Scan platform AZ actuator stuck (8/26/81): later fixed

Planets

	Closest Approach Date	Closest Approach Altitude (km)	Total Number of Images Returned
Jupiter			
Voyager 1	3/5/79	277,400	18,800
Voyager 2	7/9/79	650,180	14,900
Saturn			
Voyager 1	11/12/80	123,910	13,550
Voyager 2	8/25/81	100,830	11,850
Uranus			
Voyager 2	1/24/86	81,440	5,839

Moons

(Voyager best imaging, resolutions in km)

	Voyager 1		Voyager 2	
Jupiter	Io	1	Europa	4
	Callisto	2+	Ganymede	1
	Amalthea	8		
Saturn	Titan	1	Enceladus	2
	Rhea	1	Tethys	2
	Dione	3	Hyperion	9
	Mimas	2	Iapetus	17
			Phoebe	38
Uranus			Miranda	<1
			Titania	7
			Ariel	2+
			Umbriel	11
			Oberon	12

Neptune and Triton

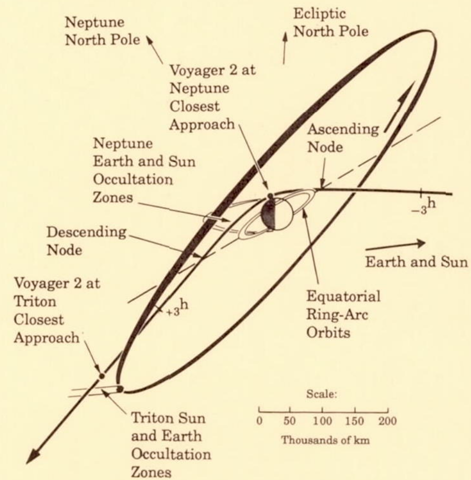
	Neptune	Triton
Equatorial Radius (km)	24,781	1500
Mass (kg)	1.023×10^{26}	9.273×10^{22}
Rotation Period (days)	0.729	5.88
Orbital Period	165 years	5.88 days
Mean Distance from Sun or Planet (km)	4.504×10^9	354,620
Suspected Composition		
Atmosphere	Mainly H,He	Mainly CH_4, N_2
Surface	None	Mainly CH_4, N_2
Interior	CH_4, NH_3 and H_2O	Unknown

Key Events

	Neptune Enc. Rel.*	ERT PDT**	Distance from Body Center (km)
Nereid--Best Imaging	-11 h 20 m	8/24 2:04 p.m.	4,680,794
Inbound Ring Plane Crossing	-57 m	8/25 12:09 a.m.	78,376
Neptune-- Closest Approach	0	8/25 1:06 a.m.	29,183
Neptune--Earth Occultation Ingress	+6 m	8/25 1:12 a.m.	30,453
Neptune--Earth Occultation Egress	+55 m	8/25 2:01 a.m.	76,831
Outbound Ring Plane Crossing	+1 h 30 m	8/25 2:36 a.m.	115,933
Start Triton Mapping	+2 h 05 m	8/25 3:11 a.m.	210,400
Triton--Best Imaging	+4 h 40 m	8/25 5:46 a.m.	53,302
Triton--Closest Approach	+5 h 14 m	8/25 6:20 a.m.	39,981
Triton--Earth Occultation Ingress	+5 h 43 m	8/25 6:49 a.m.	50,556
Triton--Earth Occultation Egress	+5 h 47 m	8/25 6:53 a.m.	53,556

**Time relative to Neptune Closest Approach*
***Time signal is received at Earth, Pacific Daylight Time*

Encounter Trajectory Plane View



Voyager Interstellar Mission

Voyager 1 and Voyager 2 will continue to sample the interplanetary/interstellar media and solar wind, search for the location of the heliopause, and observe various ultraviolet sources among the stars. Power is expected to last until 2017, and propellant until 2035. Data will be sent back early in the mission at rates as high as 4800 bits per second, and late in the mission at 46-2/3 bits per second. Voyager 1 is heading towards the constellation Hercules, and Voyager 2 southwest of the constellation Sagittarius.

HIGHLIGHTS OF DATA RETURNED FROM VOYAGER 2 NEAR NEPTUNE CLOSEST APPROACH

TIME OF DATA RECEIPT AT EARTH, PDT

* = OBSERVATIONS ORIGINALLY STORED ON VOYAGER-2's TAPE RECORDER, PLAYED BACK LATER, AND RECEIVED ON EARTH AT THIS TIME.