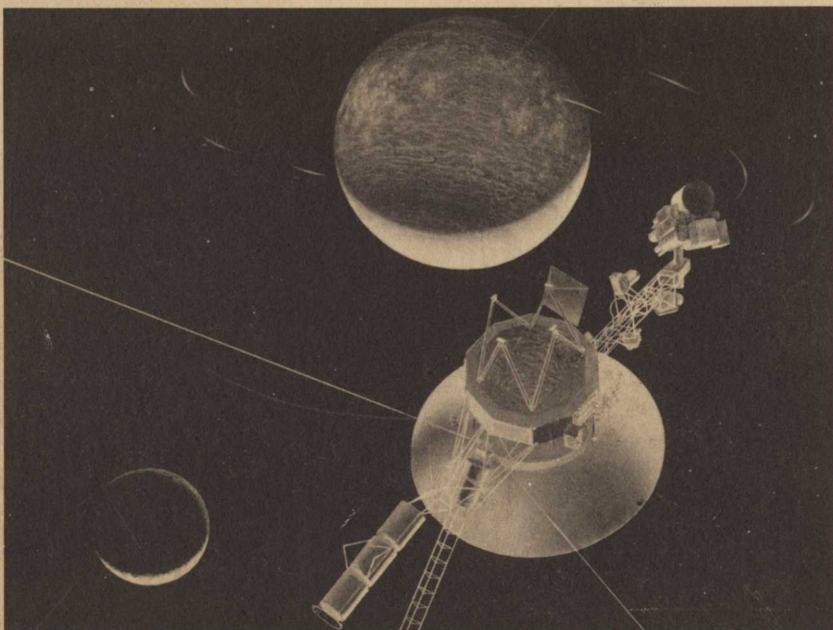
JPL Publication 89-24

The Voyager Neptune Travel Guide



June 1, 1989

NASA
National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

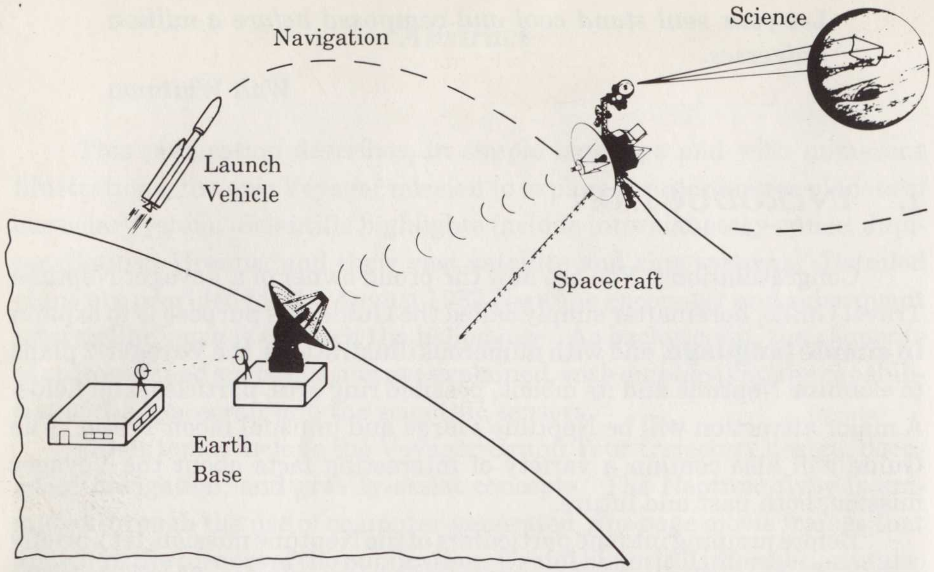


Figure 1-1. These are the five basic elements of an unmanned space mission. Earth Base is composed of a large complex of people, computers, communication lines, and tracking antennas. A manned space mission has a sixth element, the human crew for whom life support systems are required.

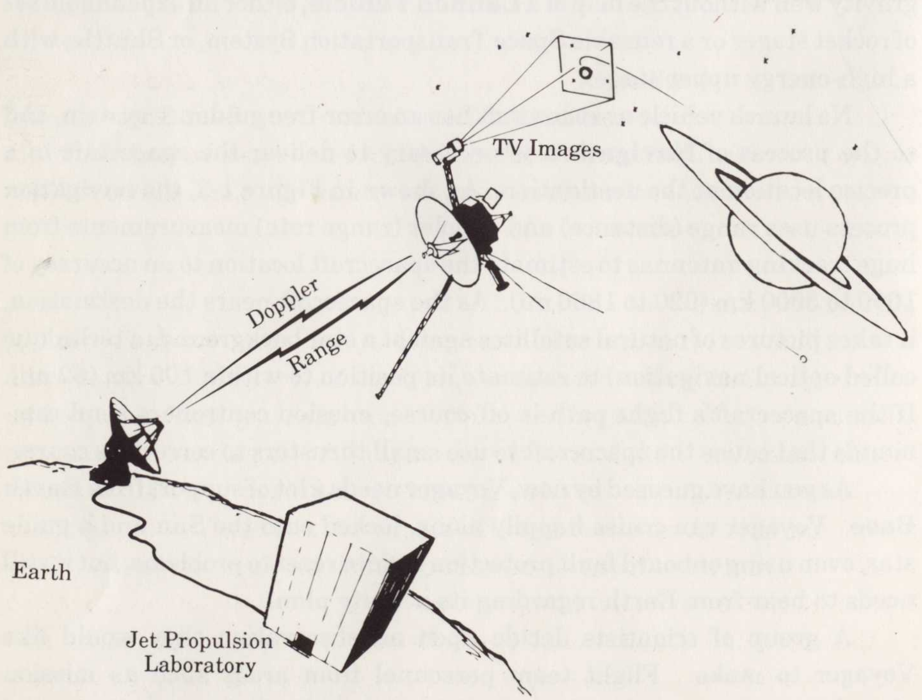


Figure 1-2. Navigators from Earth Base use radio tracking data and satellite-star images to estimate Voyager's position and heading.

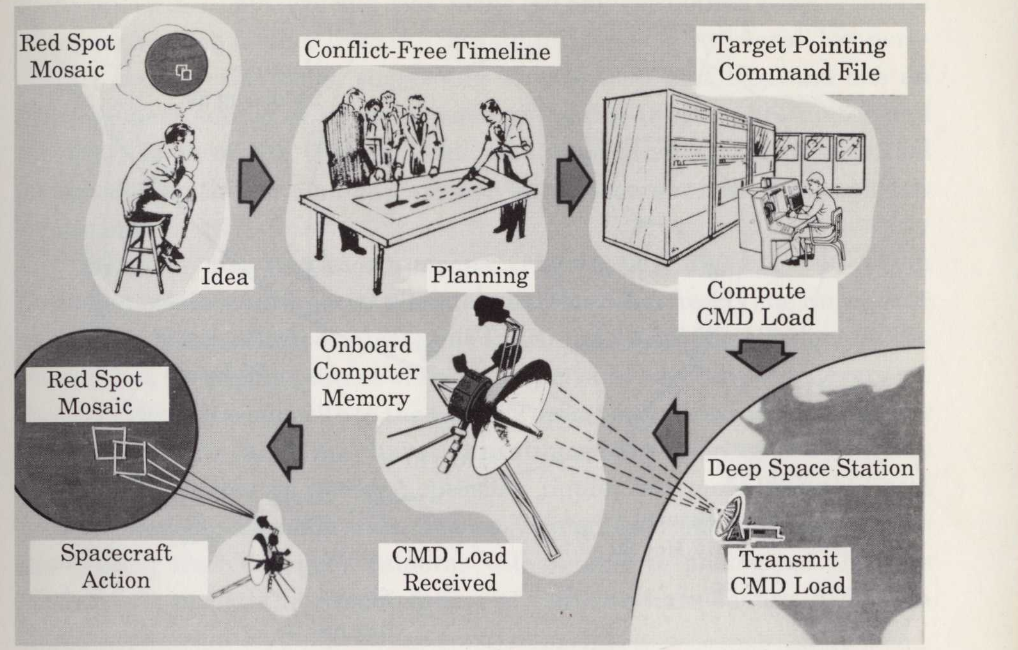


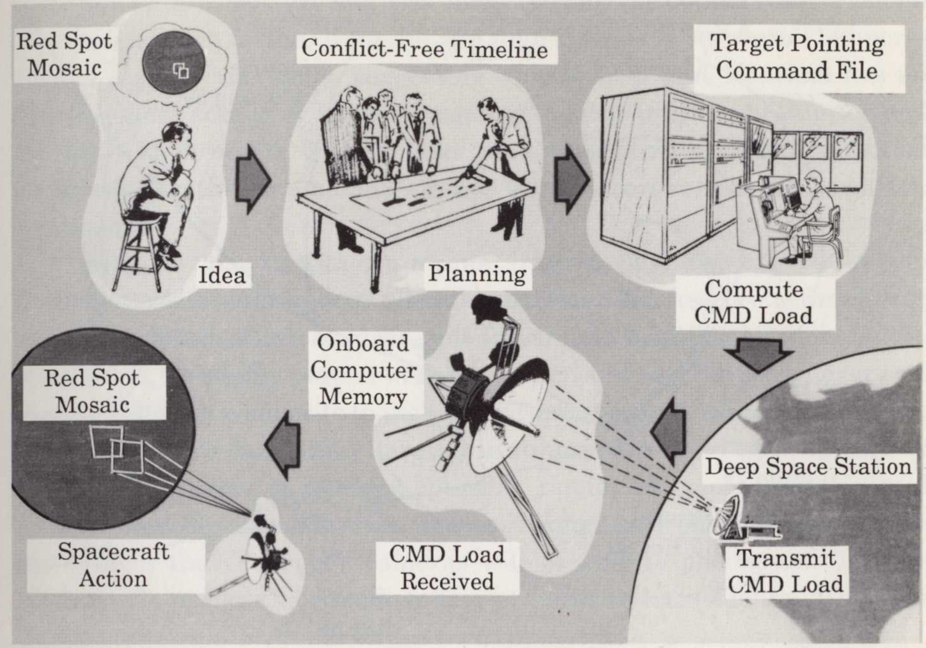
Figure 1-3. Many steps are necessary to develop activity sequences that Voyager will eventually execute.

Benny Macias Pena

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.



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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

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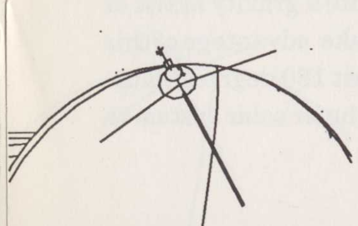

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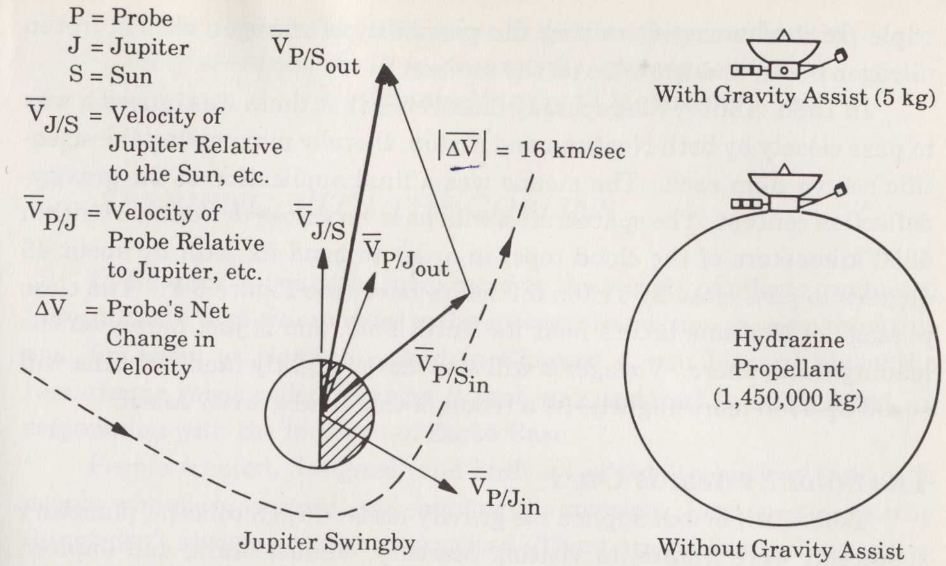

Figure 7-2. Passing close by a massive body causes a spacecraft's path to be bent, and energy to be exchanged between the spacecraft and body. In the Voyager-1 Jupiter swingby shown, there is no net speed gain relative to Jupiter; however, Voyager 1 gained 16 km/sec (35,700 mph) relative to the Sun, 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

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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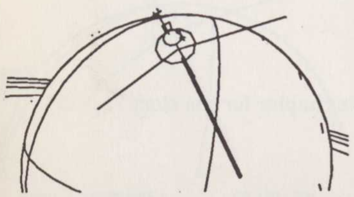

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Past skirmishes with the goblins have inflicted their wounds on both spacecraft; fortunately (since it is going to Neptune), Voyager 2 is probably the healthier of the two, considering that both of its FDS memories are still usable. Table 8-1 summarizes 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 • Receiver 2 signal lock circuit	• 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
• 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

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.)*

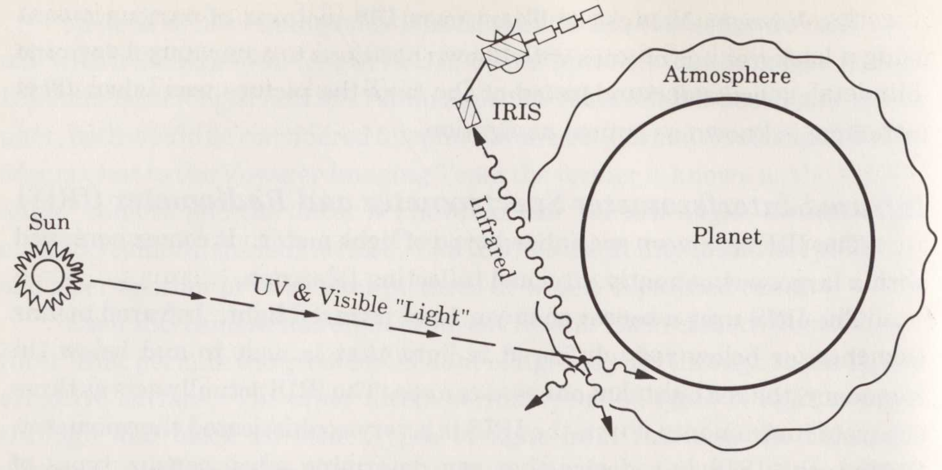


Figure 5-1. The planet absorbs the visible and ultraviolet energy from "sunlight," then emits infrared "light" which the IRIS can "see." Certain molecules in the cooler, overlying atmosphere absorb some colors of infrared "light."

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.

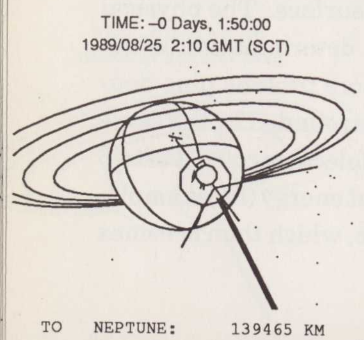
Each atom or molecule will emit or absorb energy of one or more colors. It is known from laboratory studies what colors are emitted or absorbed by a particular element or compound. To detect this element or compound, all you have to do is see the appropriate color or colors being emitted or absorbed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

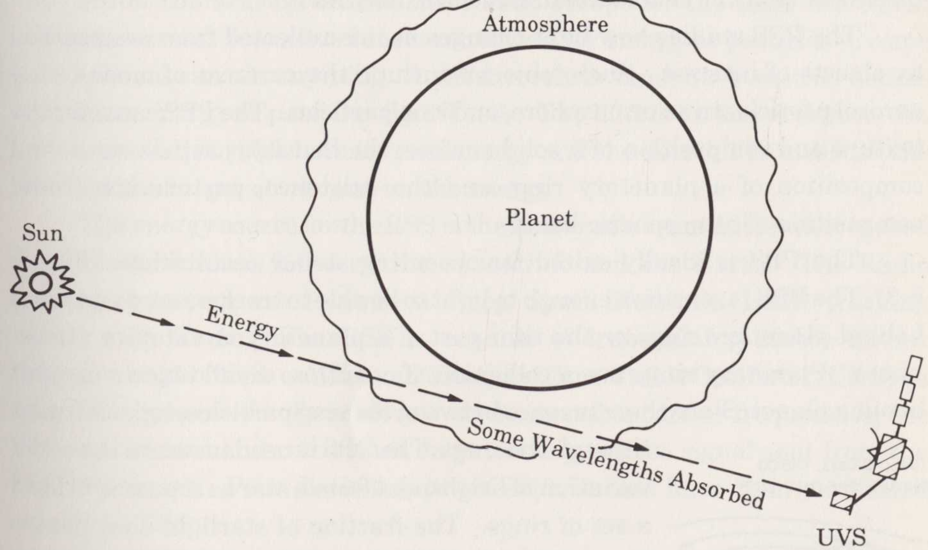


Figure 5-2. Certain molecules in the atmosphere can absorb particular wavelengths from the Sun's energy, and the UVS can spot these missing "lines."

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.

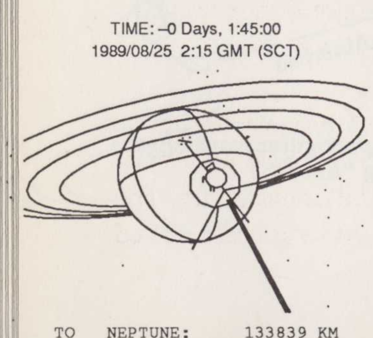
Photopolarimeter Subsystem (PPS)

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



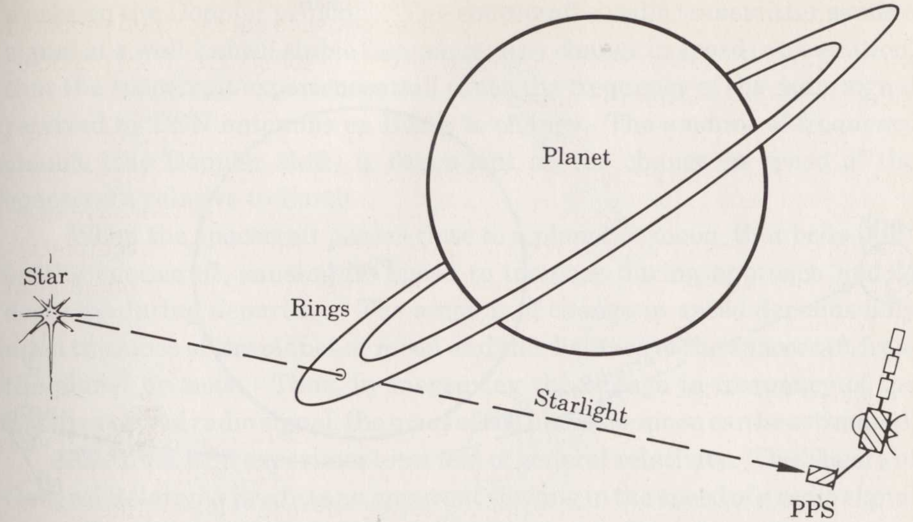


Figure 5-3. Like watching a flashlight moving behind a partially transparent picket fence, the PPS can accurately measure the amount of starlight passing through a planetary ring system.

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

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.

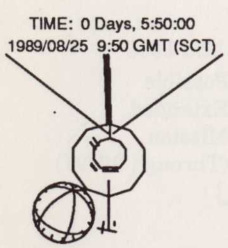
The mission's chief purpose is to study the surface, atmosphere and climate of Mars throughout a full Martian year of 687 Earth days. Imaging from an orbit lower than that of the Viking orbiters, the Mars Observer Camera will produce panoramic, high-resolution surface maps—useful for planning future 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



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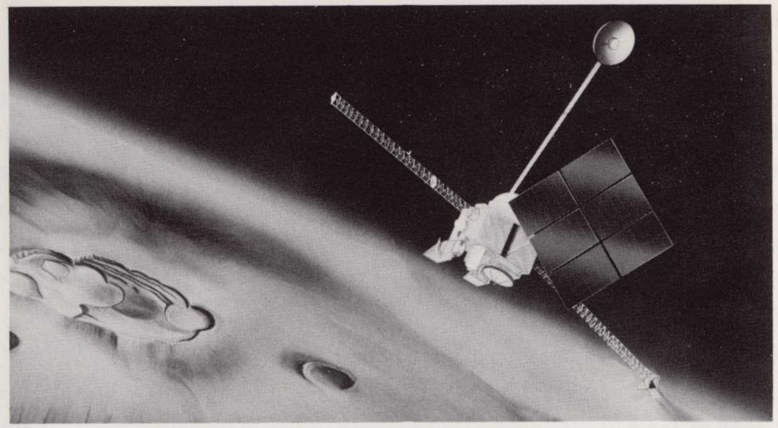
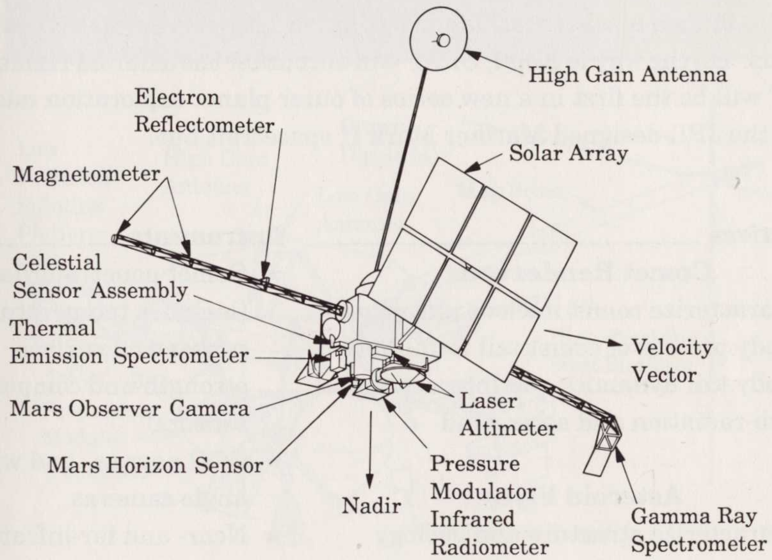
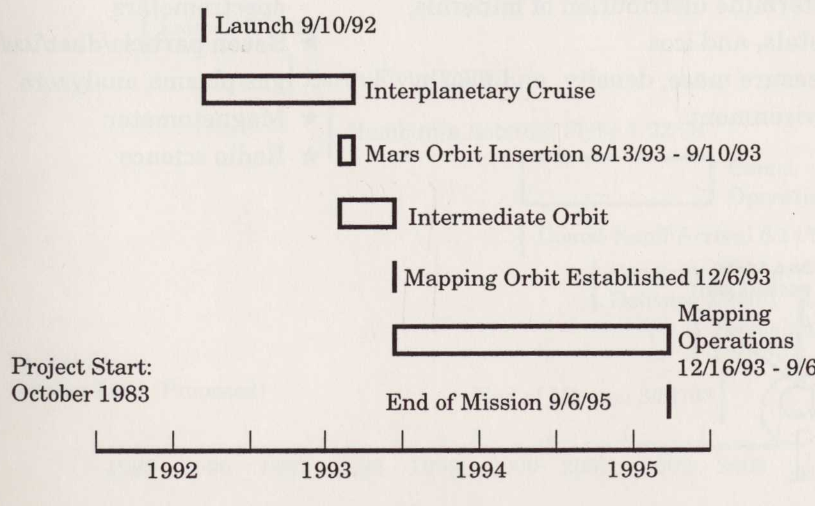






Ulysses

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

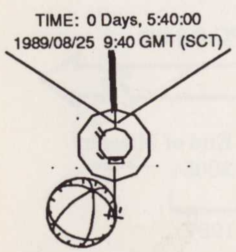
Instruments

★ 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



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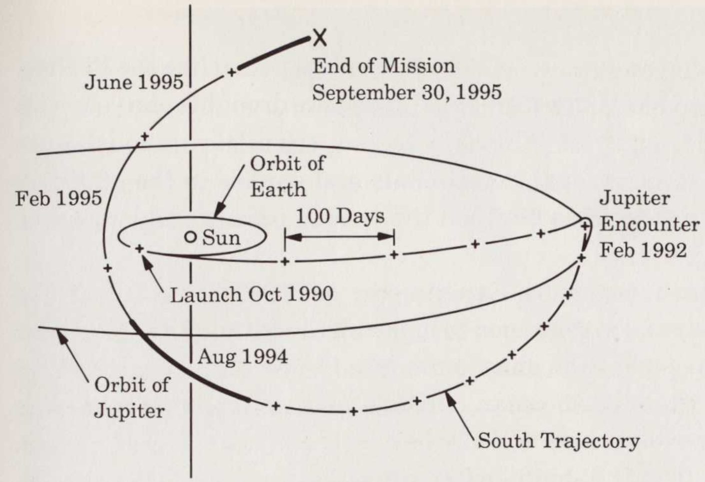
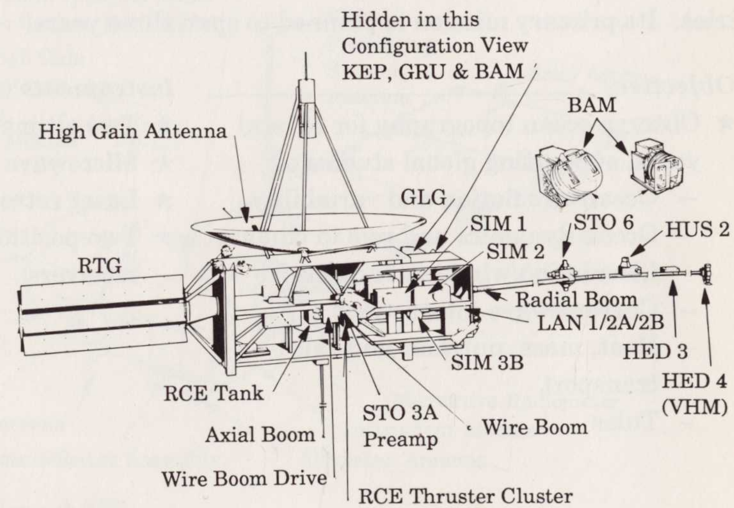
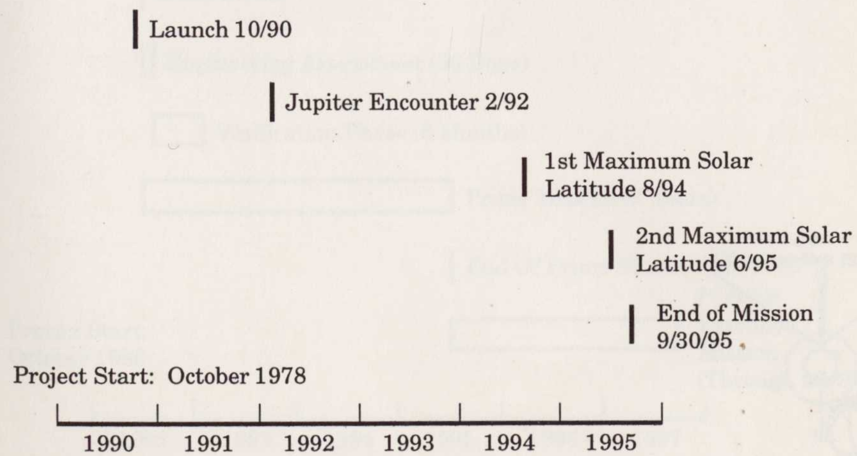


250 Days Above 70°, Maximum Latitude 85°





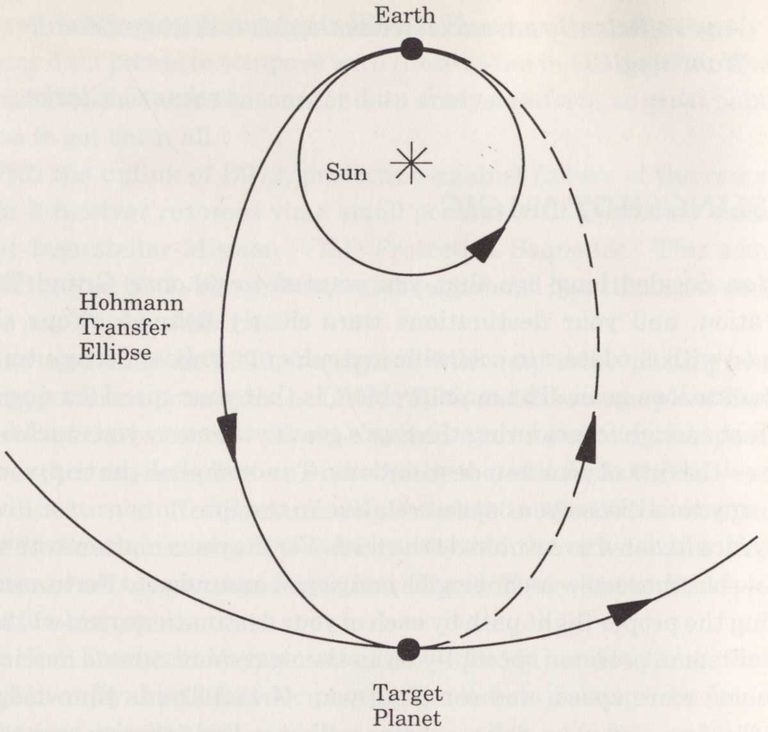
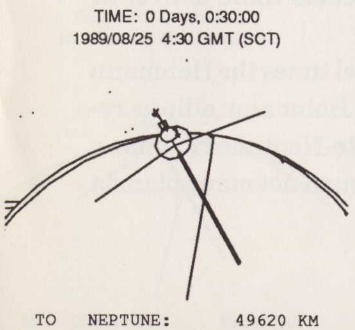


Figure 7-1. A Hohmann transfer ellipse, tangent to the orbits of both the planet one is leaving and the planet one is going to, requires the least departure energy or speed.

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.

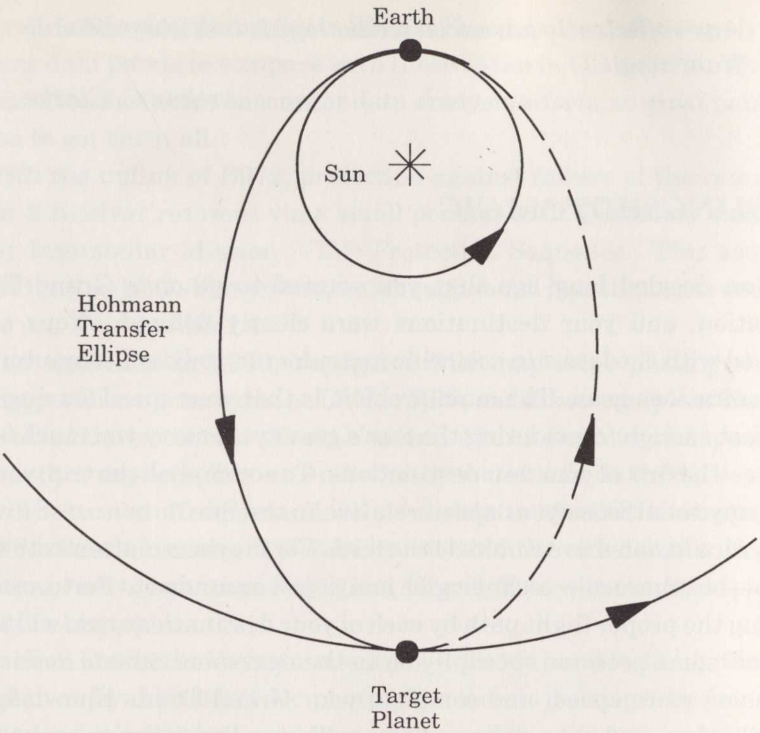


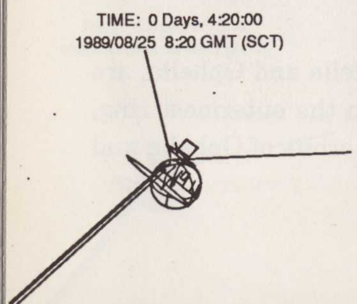
Figure 7-1. A Hohmann transfer ellipse, tangent to the orbits of both the planet one is leaving and the planet one is going to, requires the least departure energy or speed.

★ 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,

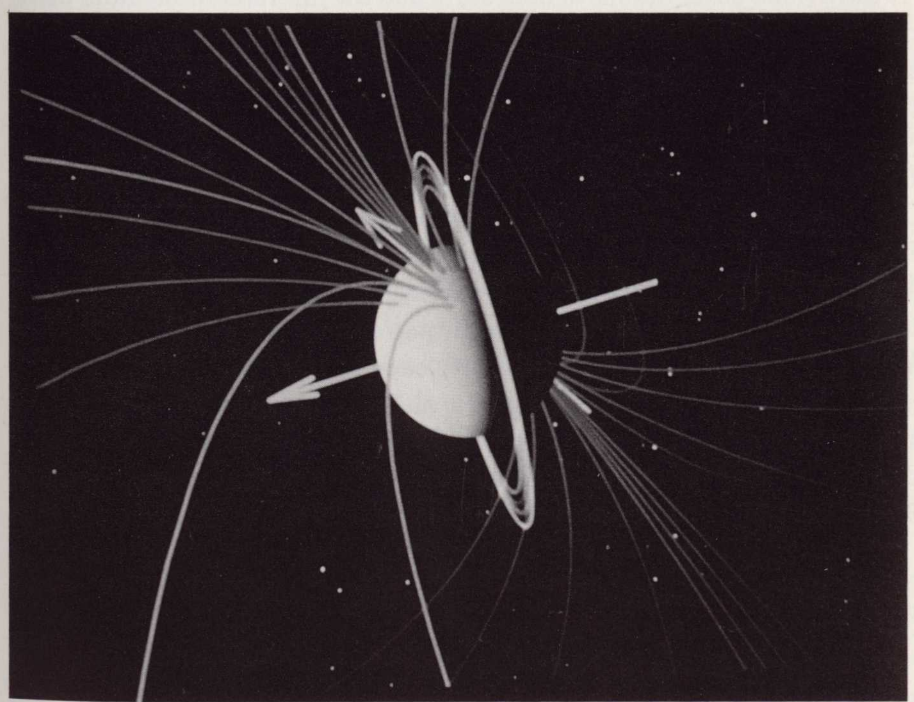


Figure 13-15. A computer-graphics reconstruction of the surprising orientation of Uranus' magnetic field. The planet's spin axis is shown pointing towards the Sun to the left; the north pole of the magnetic dipole points to the upper left.

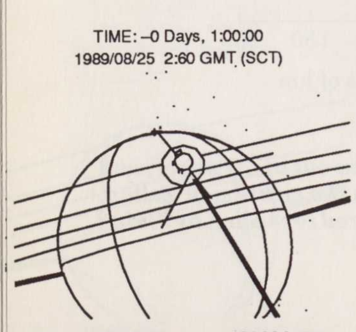
An added bonus (and complication) at Neptune is that, for the first time on the Grand Tour, we are free to target Voyager 2 to any reasonable aiming point. At Jupiter, Saturn and Uranus, we had to worry about getting to the next planet, so rigid "swingby corridor" aiming-point constraints were imposed 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

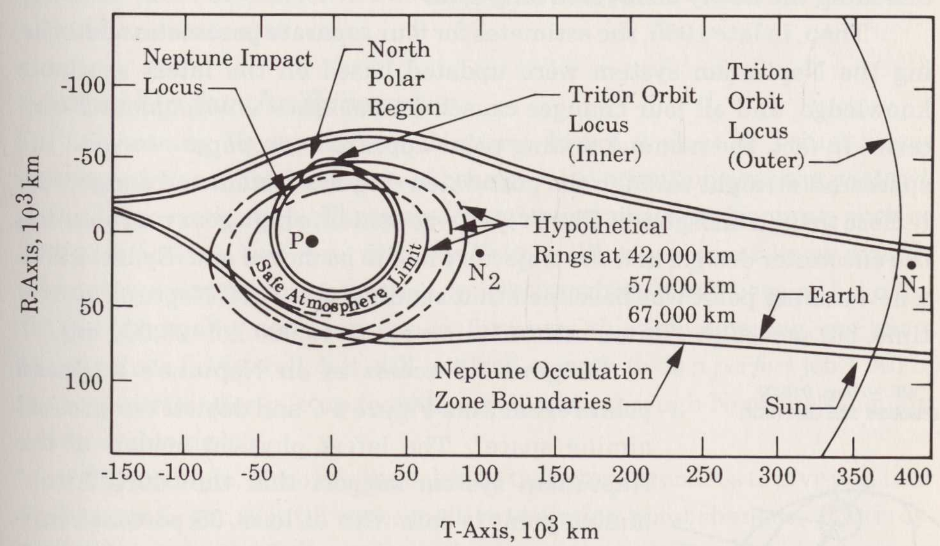


Figure 6-2. Our giant target between Voyager 2 and Neptune is shown here, marked with the Neptune aiming-point possibilities that were studied over eight years ago.

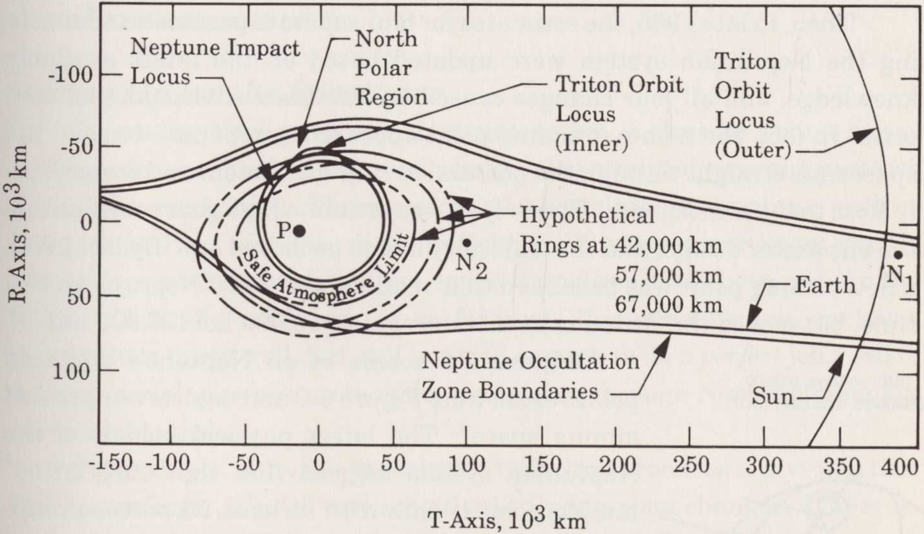


Figure 6-2. Our giant target between Voyager 2 and Neptune is shown here, marked with the Neptune aiming-point possibilities that were studied over eight years ago.

Water
ON
Mars

Michael H. Carr

Carr

Water ON Mars

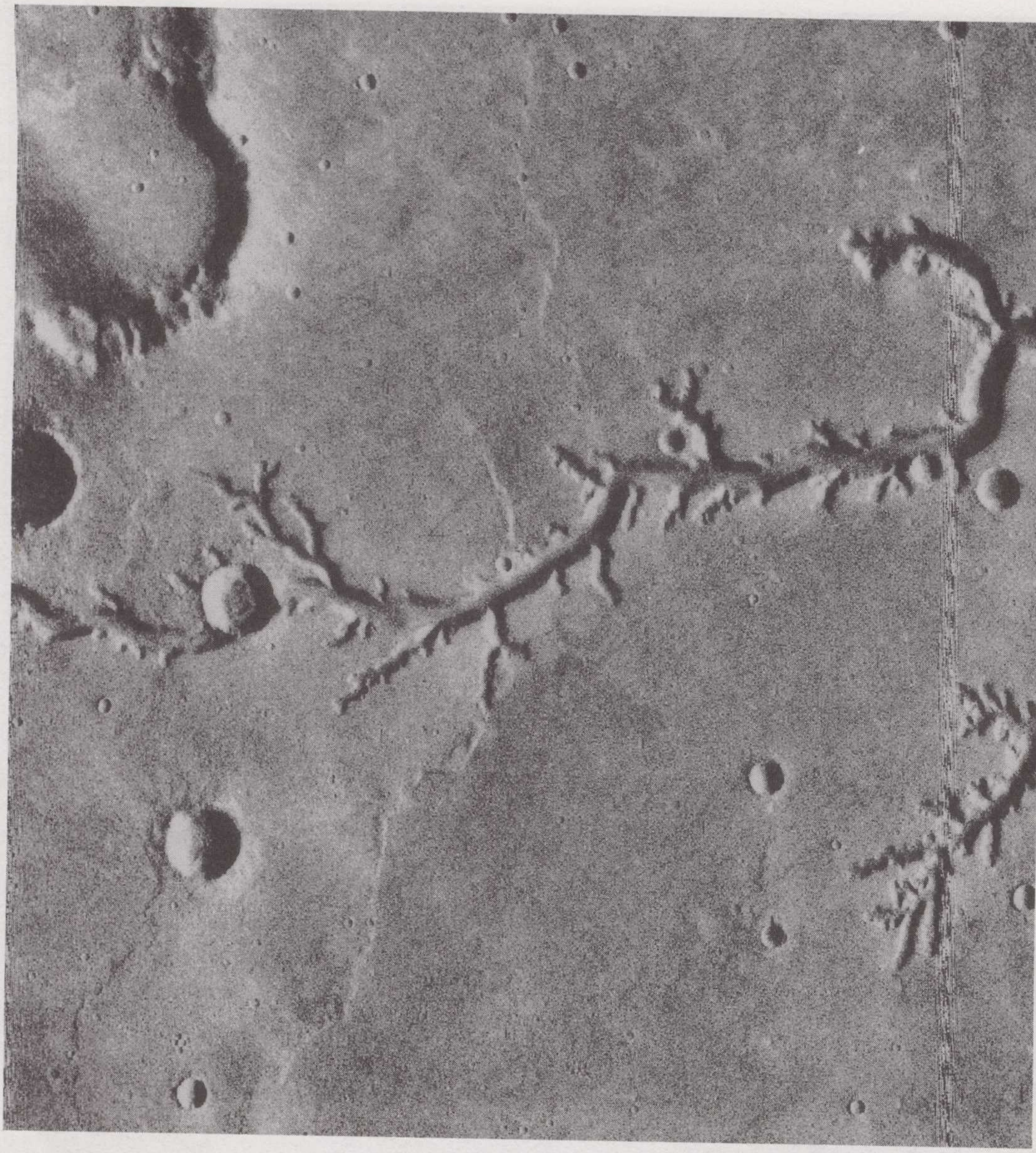


Figure 4-8. Nirgal Vallis at 27°S, 44°W, showing classic groundwater sapping patterns. Branches end in alcove-like terminations. Areas between the branches are undissected and the branching pattern is very open. The scene is 80 km across (Viking Orbiter frame 466A5).

channel. In summary, while the networks resemble terrestrial river valleys in plan and are widely interpreted as fluvial valleys, there are reasons for skepticism that they are indeed close analogs to terrestrial river valleys.

Fretted Channels

Fretted terrain is the term applied to a region along the plains-upland boundary between roughly 290-360^{0}W and 30-50^{0}N, in which the low-lying plains to the north complexly interfinger with the uplands to the south, thereby isolating numerous islands of upland surrounded by 1–2 km high escarpments (Sharp, 1973). Almost everywhere within the fretted terrain, debris aprons (Figure 4-12, with sharply defined flow fronts and convex-upward surfaces, extend from the escarpments across the adjacent plains for distances up to 20 km (Squyres, 1978). The debris

Figure 4-9. This high resolution view of a 2–km wide valley on the equator at 260°W is typical of valley networks in the uplands. The valleys have flat floors and steep walls and most lack smaller, narrower tributaries. Tributaries, if present, are commonly like the vague depression in the middle right of this image (Viking Orbiter frame 131S17).

aprons have been ascribed to mass wasting abetted by entrained ice. Of primary interest here is the origin of broad (up to 20 km wide), flat-floored, steep-walled channels, termed *fretted channels*, that reach deep into the upland (Figure 4-13), for they, like the debris aprons, may have formed largely as a consequence of mass wasting. The fretted channels branch upstream, as do valley networks. They differ from the valley networks in being much wider and in displaying abundant evidence for mass wasting.

The debris aprons surrounding mesas and massifs, and on the valley walls, are the most recent products of erosion in the fretted terrain. Crater counts of Squyres (1978) indicate that those in Nilosyrtis date from roughly the base of the

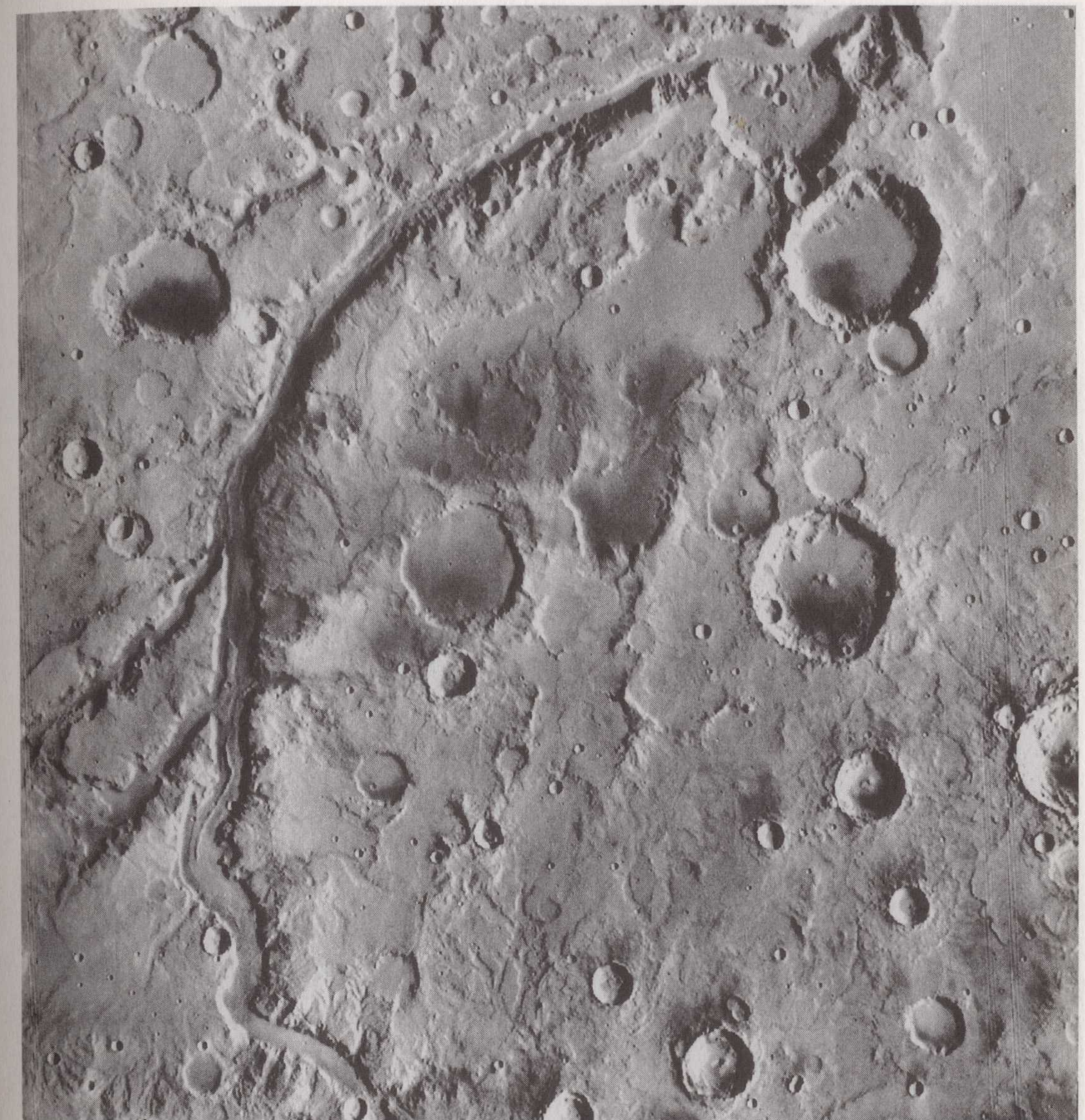


Figure 4-10. Ma'Adim Vallis at 24°S, 182°W is one of the largest valley networks on the planet. A central ridge along part of its length resembles a median moraine. The size of the valley is difficult to reconcile with the modest drainage area and small number of tributaries. The scene is 250 km across (Viking Orbiter frame 597A20).

Amazonian. Others may be even younger. A major question is whether the processes that formed the debris aprons are also responsible for the gross dissection of the fretted terrain to produce the complicated pattern of mesas and channels. Where unconfined the debris aprons have clearly delineated outer margins roughly 20 km from the source. The aprons may be presently active and still moving, having reached only 20 km from their source because of the limited time since they started to flow. Alternatively, the aprons may be stable, having reached an equlibrium configuration. Irrespective of which alternative is true, the most recent episode of mass wasting represented by the debris aprons is unlikely to be responsible for formation of the fretted terrain. To form the fretted terrain, material must be transported for distances far greater than 20 km,

Figure 4-13. Typical fretted channel at 32°N, 341°W. Fretted channels are wider than typical valley networks and, unlike outflow channels, most branch upstream. They generally contain abundant evidence of mass wasting. The channel here is 8 km across for most of its length (Viking Orbiter frame 567A23).

from Ganges Chasma to Shabaltana Vallis. Completely enclosed channels also suggest subsurface erosion and/or solution, and the former movement of groundwater in the region.

Many of the fretted channels have attributes, such as alcove-like terminations of tributaries, U-shaped or rectangular-shaped cross sections, and no dissection of interfluves, which suggest headward erosion by sapping (Figure 4-15). However, none of the fretted channels show evidence of fluvial erosion. They do not contain river channels, and the complex texture of their floors indicates clearly that the flat floors are not floodplains, although collapse of the surface in places to form linear depressions suggests subsurface flow.

One possibility is that the fretted terrain formed mostly early in the planet's history, mostly as a result of mass wasting along scarps, accompanied by water-lubricated creep of the re-

Figure 4-14. Detail of the top of the previous figure. The linear depression on the left appears to have formed by collapse, suggesting subsurface drainage. Compare with Figure 3-3. The texture on the floor of the 6-km wide channel on the right is typical of fretted channels (Viking Orbiter frame 205S16).

sulting debris (Figure 4-16), and subsurface erosion and solution (Carr, 1995). Preferential mass-wasting by sapping at valley heads may have created the valleys, the sapping process being aided by groundwater seepage into the mass-wasted debris. Flow of water across the surface may not necessarily have been involved; the debris could have flowed down the developing valley, away from the valley head, also by mass-wasting. Headward extension of the valleys would have been favored by the convergence of groundwater flow, and the consequent enhanced undermining of slopes at valley heads, loosely analogous to the way that terrestrial fluvial valleys extend themselves by groundwater sapping (Dunne, 1980). Then, as conditions changed, because of a declining heat flow, but also possibly because of climate change, the 273 K isotherm may no longer have intersected the base of the debris flows, and the former liquid-lubricated flows would have stabilized (Figure 4-16). Talus subsequently shed from escarpments would have formed the viscous, markedly convex-upward, probably ice-lubricated flows that we currently observe, the ice being derived from ground ice in the uplands (Lucchitta, 1984). The transition from water lubricated to ice lubricated flows would have resulted in a major decline (to almost zero) in the rates of scarp retreat, planation, and headward erosion of the valleys. Formation of fretted terrains along the plains upland boundary in the 30-45°N latitude belt may have been favored by large local relief, drainage of groundwater northward toward the plains-upland boundary (Figure

Figure 5-13. Mass wasting along the northern edge of the volcano Hecates Tholus, which is situated off the bottom of the picture. Volcanic materials at the surface appear to have slid to the north, down the regional slope. The simplest explanation is that movement of the rigid, near-surface, volcanic materials was facilitated by buried, ice-rich deposits. The picture is 42 km across (Viking Orbiter frame 86A35).

Miscellaneous

Other features have variously been interpreted as pingos, as pseudocraters that form by explosive eruptions when lava is deposited over ice-rich ground, and as table mountains, which are flat-topped, steep-walled volcanic edifices that form when a volcano grows through thick ice deposits (see below under volcano-ice interactions).

Glaciers

Glaciers are not truly ground ice, but it is useful to mention them in this context. The possibility that outflow channels could have been cut by glaciers, as proposed by Lucchitta (1982), was mentioned briefly in Chapter 3. Lucchitta pointed out the strong resemblance both in morphology and scale between terrestrial glacial features and

Figure 5-14. Possible thermokarst at 23°N, 35°W. Irregular hollows have been etched out of the higher standing areas. Some of the hollows have merged to form valleys. The scene closely resembled terrestrial thermokarst caused by removal of ground ice. The scene is 45 km across (Viking Orbiter frame 8A74).

martian outflow channels. She envisaged spring fed glaciers, the springs creating massive icings that ultimately grew thick enough to move down pre-existing valleys and carve the large outflow channels. Recently a more radical suggestion has been made by Kargel and Strom (1992) that extensive glaciations have occurred relatively late in martian history. They draw analogies between a variety of martian landforms and terrestrial glacial features. Two landforms, which they describe as eskers and terminal moraines, are particularly intriguing. Eskers are narrow, sinuous, branching ridges of sand and gravel deposited from subglacial streams. They have the planimetric form of a stream channel but are positive relief features, left standing after the ice has disappeared. Esker-like ridges occur in several places on Mars, including near the south pole (Figure 5-16), within the Argyre basin, and adjacent to thick, easily erodible deposits along the plains-upland boundary, south of Elysium Planitia. The resemblance between ridges in these areas and terrestrial eskers is very striking. The putative terminal moraines are found mainly in Hellas and the northern plains and were mentioned earlier under patterned ground (see Figure 5-12). Kargel and Strom describe several other landforms in glacial terms but the case for a glacial interpretation is far less strong than with the "eskers" and "moraines."

It is vitally important for the climatic history of the planet to know whether these are indeed no evidence of andesitic volcanism from the SNC meteorites, and the analyses of the soils at the Viking landing sites are consistent with a basaltic source, so intepretaiton of the pyroclastic deposits as the result of phreatomagmatic activity (reaction between magma and groundwater or seawater) is plausible.

Given an extensive groundwater system and sustained volcanic activity, hydrothermal activity must have occurred repeatedly throughout martian history. Heat sources may also have been provided by large impacts. As we saw in the previous chapter, hydrothermal activity has been invoked to explain valley networks on volcanoes (Gulick and Baker, 1990) and around impact craters (Brackenridge et al., 1985). In a typical hydrothermal system, a buried heat source warms groundwater which rises in a column over the heat source. When the column reaches the near-surface it spreads out laterally so that a mushroom shaped volume of warm groundwater is formed. The warm water rising from depth is replaced by cool water flowing in from the sides. Typical water circulation times are 10^4–10^5 years. Because of their biologic interest, hydrothermal systems are discussed further in Chapter 8.

Summary

A general muting of the terrain and presence of debris aprons at high latitudes suggests the presence of abundant ice at shallow depths. The absence of these features at low latitudes suggests that at the end of the Noachian the near-surface materials were ice poor or became so thereafter on time scales that are short compared with the time scales needed to modify the terrain significantly by creep. Onset diameters for rampart craters suggests ice-rich materials persisted at low latitudes much longer, and possibly to the present, at depths of a few to several hundred meters, but this conclusion is perhaps tainted by the possibility that rampart craters are the result of atmospheric effects rather than the effects of ground ice. In the low-lying northern plains, at the ends of outflow channels, a wide array of features, including polygonally fractured ground, unique ejecta patterns, possible thermokarst, and strong albedo contrasts between ejecta and local terrain, suggest the presence of thick ice deposits and/or ice-rich sediments. In view of Mars' volcanic history, we ought to see evidence of volcano-ice interactions if ice and groundwater are abundant near the surface. Outflow channels starting at volcanoes, fluvial features emerging from under lava flows, channels in volcano flanks, thick ash deposits on and around volcanoes, and features resembling terrestrial table mountains and moberg ridges have all been cited as examples of such interactions.

6 CLIMATE CHANGE

This chapter discusses two very different aspects of climate change. The first concerns changes induced by quasi-periodic variations in the orbital and rotational motions of the planet. These changes occur on relatively short time scales, have likely occurred throughout the history of the planet and so been superimposed on any long-term changes. Unless there are large amounts of exchangeable CO_2 sequestered in the polar layered terrains or the remnant caps, such periodic changes are likely to be small. Much of the discussion on quasi-periodic changes focuses not on observational evidence, but on hypothetical arguments as to what effects variations in the astronomical motions might have on various processes such as transport of dust and exchange of CO_2 between the regolith, atmosphere, and poles. While layering in sediments at the poles has been attributed to modulation of deposition and erosion by changes in surface conditions induced by planetary motions, the connection between the layered terrains and planetary motions has not been unequivocally established. In contrast, we have abundant observational evidence that Mars might have undergone long term, secular climate changes. We have already discussed at length some aspects of the evidence, the presence of valley networks, but erosion rates provide additional, possibly stronger, support for the supposition that conditions on Mars early in its history were very different from those that prevailed during most of its subsequent history. We will examine the timing and climatic implications of valley network formation and changes in erosion rates, then explore how the implied climatic conditions might have been attained.

Quasi-Periodic Climate Change

Changes in orbital and rotational motions

Periodic changes in the pattern and intensity of martian seasons can result from changes in the orbital and rotational motions of the planet. Eccentricity causes an asymmetry in the climatic regime of the two hemispheres. At present Mars is closer to the sun during southern summer, so southern summers are shorter and hotter than those in the north. In addition, dust storms commonly start during southern summer, some reaching global proportions. During northern summer the threshold for initiation of global dust storms is not reached, almost certainly because of the lower temperatures that result from the greater distance from the Sun. Dust storms affect atmospheric temperatures, circulation patterns, and transport of water. They may also affect the albedo of the seasonal and residual caps, thereby affecting their stability. They thus have broad climatic significance. The present eccentricity is 0.093, but during the present epoch it varies between about 0 and 0.13 (Ward, 1992). Short-term variations with a period of 10^5 years are superimposed on longer variations with a period of approximately 2 Myr (Figure 6-1). The range of 0–0.13 is approximate because extrapolations backward in time become very uncertain for times greater than 10^7 years. On time scales of this length or longer, the eccentricity may drift to higher values and becomes unpredictable. At low eccentricities climatic differences between the two hemispheres are small; at high eccentricities differences between the two hemispheres can be significant, as they are today.

A second motion that causes periodic changes in the seasonal patterns is precession, the slow conical motions of the spin axis of the planet and the normal to the orbit plane. The Mars spin axis precesses with a period of about 173,000 years and the axis to the orbit plane precesses with a period of roughly 70,000 years (Ward, 1973). These motions cause rotations in the line of equinoxes and the line of apsides (see Figure 1-1), both with respect to inertial space and to each other. The net effect is to cause an alternation of

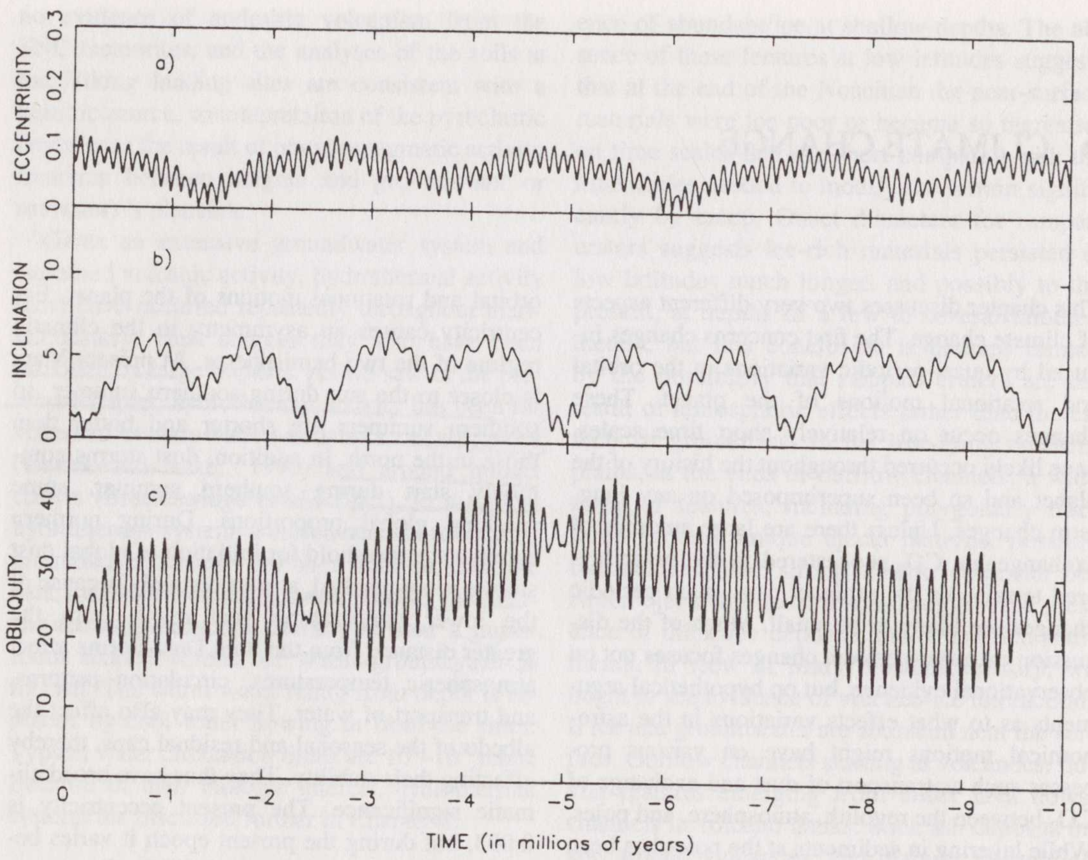


Figure 6-1. Eccentricity, inclination, and obliquity for the last 10 Myr, according to the orbit theory of Laskar (1988). Calculations vary significantly with very small changes in the initial conditions assumed. (From Ward, 1992. Reproduced with permission from the University of Arizona Press.)

the climatic regimes of the two hemispheres with a period of 51,000 years. Precession of the spin and orbital motions control the season at which perihelion occurs, and hence which hemisphere has the warmer, shorter summers.

Changes in obliquity are likely to have much larger climatic effects than the current variations in precession and eccentricity just described. The obliquity is the angle between the spin axis and the normal to the orbit plane. The present obliquity is 25.19°, but it undergoes large changes. During the current epoch, it is thought to oscillate between 13° and 42°, about a mean of 24° (Ward, 1992). The oscillations have a period of 1.2×10^5 years and an amplitude that is modulated on a 2 Myr cycle (Figure 6-1). There are considerable uncertainties as to what past obliquities were (Ward, 1992; Laskar and Robutel, 1993; Touma and Wisdom, 1993). Minute differences in the starting values for the calculations of past motions lead to very large differences in the solutions when projected backward (or forward) in time, such that projections larger than 10 Myr have little meaning.

Obliquity variations are inherently chaotic on time scales of 10 Myr or longer. Part of the problem concerns resonances. If the period of precession of the spin is commensurate with one of the periods of variation of the orbit, then spin orbit resonances can occur. Excursions in obliquity significantly larger than are suspected from the current oscillations are then possible. Thus, secular changes in the orbital parameters can cause major changes in the precessional and hence the obliquity motions. All these variations cause the obliquity to be chaotic, at least on time scales greater than 10^7 years. Over geologic time values for the obliquity may have occasionally reached as low as 0° and as high as 60° (Laskar and Robutel, 1993; Touma and Wisdom, 1993). In

this respect Mars differs from the other terrestrial planets. The obliquities of Mercury and Venus have been stabilized by tidal dissipation, and that of the Earth by the presence of the Moon.

Long-term changes can also be induced by the planet itself. Precession of the spin axis, for example, may change with time as a result of geophysical changes. The precessional period is given by $2\pi/\alpha \cos\theta$, where θ is the obliquity. The precession constant α given by

$$\alpha = \frac{3}{2}\left(\frac{GM_s}{\omega a^3}\right)\left(\frac{J_2}{\lambda}\right),$$

where G is the gravitational constant, M_s is the mass of the Sun, ω is the spin rate, a is the semimajor axis, $J_2 = [C - 1/2\,(A + B)]/Mr^2$, and $\lambda = C/Mr^2$. A, B, and C are the principal moments of inertia, and r is the radius of the planet. Differentiation of the planet, or the building of volcanic constructs such as the Tharsis and Elysium bulges, will have affected the moment of inertia and hence the precession. As the precession changes, so do the resonances with other motions.

Obliquity affects the distribution of solar insolation with latitude (Figure 6-2). At low obliquities, the amount of insolation received, averaged over the entire year, depends strongly on latitude, with the poles receiving almost none. As the obliquity increases, somewhat less insolation falls on low latitudes, but the amount received by high latitudes increases substantially. At an obliquity of about 50°, the annual average is almost independent of latitude. At obliquities higher than 54°, more insolation falls on the poles than on the equator. Because the poles act as storage reservoirs for volatiles at medium to low obliquities, the onset of high obliquities has the potential for injecting large amounts of volatiles, particularly H_2O and CO_2, into the atmosphere.

Potential effects of changes in orbital and rotational motions

Changes in obliquity will affect how exchangeable CO_2 and H_2O is distributed between three main reservoirs: the atmosphere, the poles, and the high-latitude regolith. Of these reservoirs, only the volatile contents of the atmosphere and seasonal caps are well known, the atmosphere from direct measurements and the seasonal caps from pressure variations in the atmosphere (Table 6-1). The residual caps are bright areas

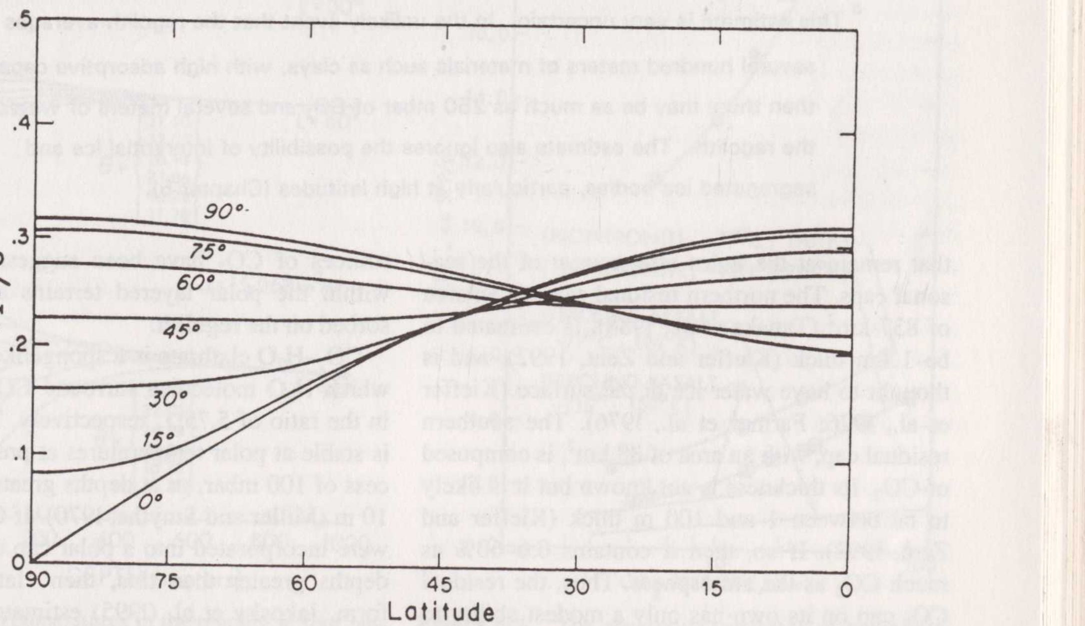


Figure 6-2. Average annual insolation <I> as a function of latitude for various values of the obliquity. The insolation is normalized to the average solar flux. At obliquities higher than 54° the average annual insolation is higher at the poles than at the equator. (From Ward, 1992. Reproduced with permission from the University of Arizona Press.)

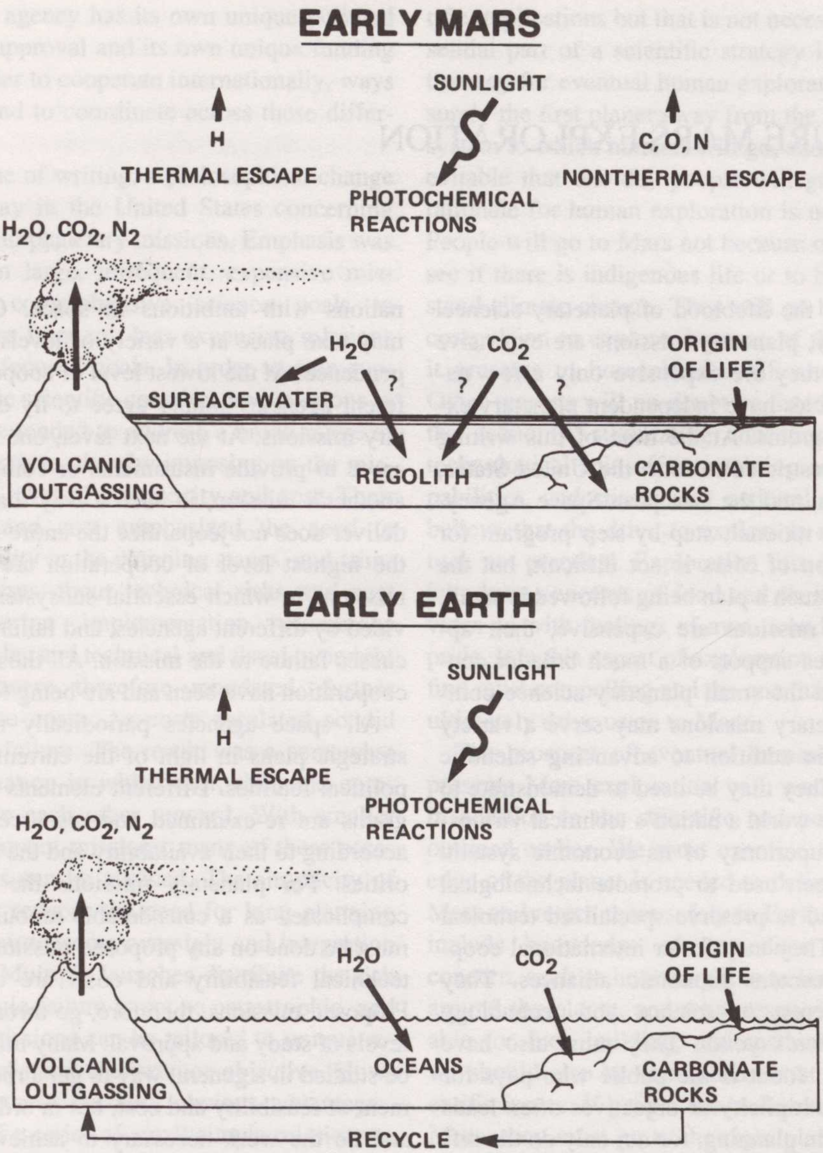


Figure 8-6. Diagram comparing early Mars with early Earth. (Courtesy R. Haberle, NASA/Ames.)

been very different. By 3.5 Gyr ago life on Earth was already diverse and complex. We do not know the environment under which life started on Earth, but hydrothermal springs and volcano-tidal interfaces are likely candidates. Early Earth and early Mars were in many ways similar (Figure 8-6). Both had high rates of impact, high rates of volcanism, abundant water, and a $N_2-H_2O-CO_2$ atmosphere. Both may have had warm climates, although this is not absolutely certain for Mars. We know life started on Earth, but we do not know what happened on Mars. Surface conditions on Mars changed around 3.5–3.8 Gyr ago, as indicated by changes in the rates of erosion and valley formation. If life did start, it would have had to adapt to the changes, and subsequent colonization of possibly rare and transient habitats would have been hindered by the harsh radiation environment at the surface. The best places to look for past life are probably in lacustrine sediments and hydrothermal deposits, which should both be common at the martian surface. Even if life never started on Mars, the search in these favored locations may provide clues concerning prebiotic chemical evolution.