Galileo spacecraft heads for Jupiter

The journey begins for an in-depth study of the greatest of the outer planets. 21st Century Science & Technology *Associate Editor Marsha Freeman reports on this upcoming planetary mission.*

Most of the total planetary mass in our Solar System is contained in one planet—Jupiter. This massive gas giant, which is about a half billion miles from Earth, has already been visited by four U.S. spacecraft. But those Pioneers and Voyagers spent only a few dozen hours at Jupiter as they flew by. The Galileo spacecraft, scheduled to be launched on Oct. 12 from the Space Shuttle orbiter Atlantis, will do a 22-month, in-depth study of the complex Jupiter system.

Scientists working on the Galileo mission have stressed that this spacecraft will not be studying simply one planet, but a planetary *system*. Around Jupiter is a complement of at least one and a half dozen moons, which forms a small planetary system around this star-like planet. The moons are pushed and pulled by the planet, and influenced by its magnetic field and complex magnetic structure.

For centuries, scientists have watched the Giant Red Spot storm system on Jupiter through telescopes. Spacecraft have found that, although this storm is obviously long-lived, it is also dramatically changing. Nearly 400 years ago the astronomer Galileo Galilei was able to discover the four largest moons of Jupiter with an early telescope, but he could not see too much detail. Voyager has shown us moons the size of small planets, with erupting volcanoes, possibly with liquid water interiors, and intense geologic activity.

Because Jupiter is so large and is relatively close to Earth, compared to the other gas giants, it has been studied extensively from the ground. But as Voyager demonstrated, there are many questions about its weather, atmosphere, moons, newly discovered ring, and magnetosphere, questions which will only be answered from close to the planet. The Pioneers and Voyagers posed many new questions about the Jupiter system. Galileo may help to answer some of them.

Galileo will be the second planetary mission launched from an orbiting Space Shuttle, following Magellan to Venus last May. It is the first to carry two radioisotope thermoelectric generators (RTGs), each of which is fueled by 24 pounds of naturally decaying plutonium-238.

Though RTGs have been used on over two dozen space missions in the past 20 years, and though there is absolutely no other way to power this spacecraft's scientific instruments and other systems on board, anti-nuclear activists have vowed to delay, stop, and/or disrupt the launch. On Sept. 28, the Christic Institute in Washington filed a request in U.S. District Court for an injunction to stop the launch of Galileo. The Florida Coalition for Peace and Justice, which has sponsored tours by Soviet "peace" activists, has stated they will try to obtain entry to the Kennedy Space Center launch site, and may have supporters get arrested when security forces prevent them from physically obstructing the countdown.

Nuclear-powered RTGs have been used in the past to send planetary spacecraft to Mars and to the outer planets. They were carried by the Apollo astronauts to power long-lived scientific experiments left on the Moon. Now, all of a sudden, the anti-nuclear activists claim practically the entire population of Florida could get cancer if the Shuttle blows up after launch. Plutonium, which these fear-mongers claim is "the most toxic substance" in the universe, is actually only dangerous if it is inhaled as small particles of a particular size, and if the particles stick to the lungs.

The RTGs have undergone a $50 million testing program, as well as tests that simulated Shuttle accidents, and fired bullets at them. Both an interagency nuclear safety review panel and the Department of Energy, which provides the space agency with the RTGs, have released detailed studies on the nuclear batteries and have declared them safe. President Bush, on the recommendation of his science adviser, has approved the Galileo launch, which is required before it can take place.

As one scientist remarked, there is greater danger that someone would get hurt from an RTG falling on him if the Shuttle blew up, than getting lung cancer from a breach of the RTG's protective container.

The most complex planetary mission

The Galileo mission is the first whose spacecraft will study an outer planet by orbiting around it, rather than just passing by. Galileo is comprised of two separate spacecraft, each with specific functions. The 2.5-ton orbiter will study the atmosphere, particles and magnetic fields, and moons of the Jupiter system over a period of 22 months. It will provide multiple, close fly-bys of the four Galilean moons over the course of several orbits that change with each encounter. A smaller, 750-pound probe will be released from the orbiter 150 days before the planned December 1995 arrival at Jupiter. This probe will enter the atmosphere of the great planet. During the 75 minutes the probe should spend descending through Jupiter's atmosphere, it will provide the first *in situ* measurements of the atmosphere of Jupiter, similar to experiments that have been done at Venus and Mars.

The Galileo mission is the most complex ever devised. When the Viking orbiters arrived at Mars, for example, they were set in an orbit which remained basically the same throughout the mission. But one of the three primary missions of Galileo is to take extremely close images and measurements of the Galilean moons. The reason for the interest in these bodies is that they are approximately the size of our Moon or of the inner planet Mercury, and they have turned out to be some of the most interesting bodies in the Solar System. In their variety and relative distance from Jupiter, they also share characteristics with the Sun's inner planets.

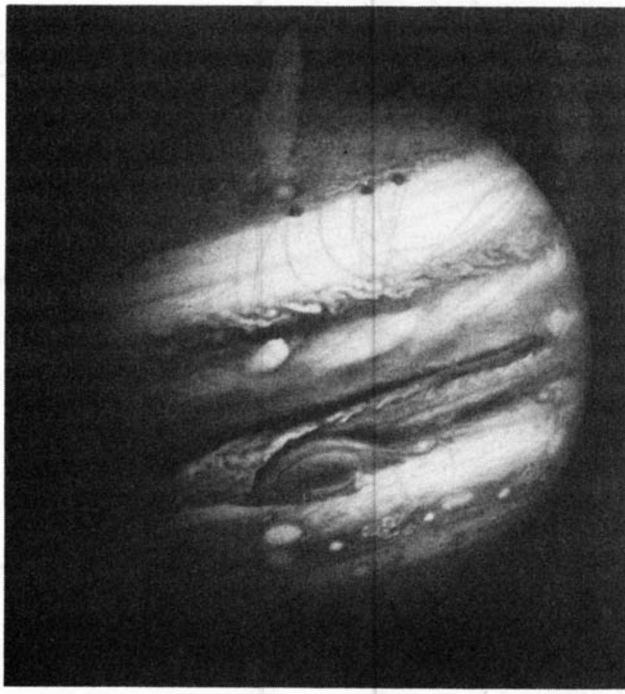
When Voyager 1 arrived near Jupiter in March 1979, it found eight volcanoes erupting on the moon Io. No active volcanoes had ever been observed anywhere in the Solar System, except on Earth. Voyager 2 also imaged active volcanoes on Io when it arrived four months later, but found that not all of the same ones were still erupting. This highly active and changing body, at only 261,400 miles from Jupiter, is pushed and tugged by the planet's massive gravity and is likely also affected by Jupiter's massive magnetic fields and trapped energetic particles. Io's surface changes so often from geologic activity that impact craters are not visible on the surface.

Surrounding Io is a cloud of neutral sodium particles which, evidence suggests, is feeding material into the huge magnetosphere of Jupiter's trapped particles. Learning more about the influence of Jupiter on Io, and vice versa, is one of the most intriguing objectives of the Galileo mission.

However, because Io is so close to the planet, the Galileo orbiter will make only one very close pass at this fascinating body. On its first orbit around Jupiter, the orbiter will pass within 600 miles of Io, or one-twentieth of the closest fly-by distance of Voyager in 1979. Galileo will resolve features on the surface down to 300 feet during its close fly-by; by comparison, the smallest features Voyager could resolve was 3 miles. Scientists will also see Io on subsequent orbits, but the risk of radiation damage to the spacecraft limits the close pass to one.

Europa, approximately twice the distance between Io and Jupiter, also shows an active geology, and evidence of tidal effects from the massive planet. Unlike Io, however, observations do not indicate volcanic sulfur on the planet, but rather water ice. Because Europa also has no significant cratering, scientists have proposed that the fracture lines that appear there mean that its surface is also re-forming, perhaps from eruptions of water from under the surface. The Galileo orbiter will come within 220 miles of Europa on its seventh orbit of Jupiter, and make additional passes farther away from the moon.

Still farther away from Jupiter, at about a twice its distance from Europa, is Ganymede, which is certainly made mostly of ice. It has a densely cratered region, and another region more sparsely cratered that has bright bands and mys-


NASA

Voyager 1 took this photo of Jupiter in February, 1979 at a distance of 20 million miles. Visible is the Great Red Spot at 20° south latitude, white oval clouds below it, the banded layers of clouds, and equatorial plumes above the dark streak of winds. Jupiter's atmosphere, weather, and storms are the most complex in the Solar System.

terious, grooved terrain. These features, again, indicate some form of geologic and perhaps tectonic activity beneath the surface.

Beautiful Callisto, which is the farthest of the Galilean satellites from Jupiter, is the most heavily cratered. It appears to be made of non-silicate, icy material, and to have undergone the least amount of geologic activity.

Information about this miniature planetary system may well provide scientists with insight into the organization and differentiation of the inner planets of the Solar System.

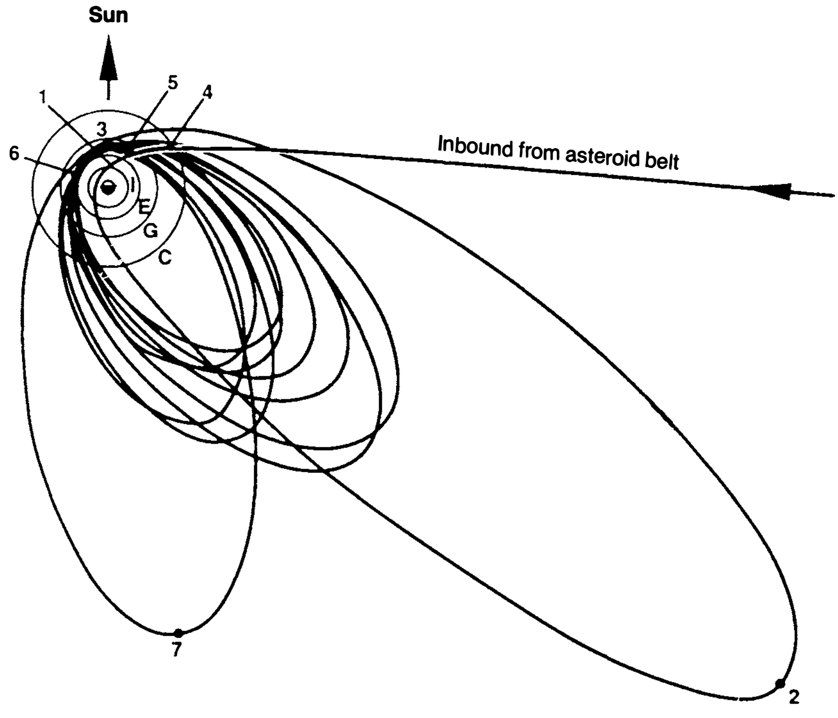
Delicate, dizzying navigational feats

But in order to acquire these close-up pictures and measurements of the moons of Jupiter, the Galileo orbiter will perform a dizzying series of gravity assists, using the gravitational pull of each moon it encounters to change its orbital trajectory slightly, and set it on the right path for its next satellite fly-by. Gravity assists have been used in the planetary program for many years. The only way the Voyager 2 spacecraft, for example, was able to fly by the four planets Jupiter, Saturn, Uranus, and Neptune, was to get a push called a "gravity assist" as it flew by each one, that would give it enough additional energy to go on to the next encounter.

Never before, however, has a spacecraft depended upon multiple gravity assists from bodies in such close proximity and so often. The navigational tricks Galileo will perform are the most complex ever attempted. **Figure 1** shows how the flight path of the orbiter will change. Each pass by a moon will either "pump up" or "pump down" the path of the orbiter, slowing it down or speeding it up. These changes in velocity cause the elliptical orbit of the spacecraft around Jupiter to change, for each one of its ten different orbits. The satellite tour pictured here is the best estimate of the orbiter's path at this time. Final adjustments to the planned encounters will be made as the spacecraft approaches Jupiter.

The detail the Galileo orbiter will see on the moons of Jupiter will be remarkable. The camera system, which uses optics similar to those on Voyager, has been upgraded by the

FIGURE 1
Galileo satellite tour



I: Io

E: Europa

G: Ganymede

C: Callisto

1: Orbit insertion and Io fly-by, Dec. 7, 1995, at an altitude of 600 miles

2: Spacecraft maneuver in first orbit to raise perijove (next Jupiter approach)

3: Ganymede fly-by July 18, 1996 at 400 miles, and again on Sept. 28, 1996 at 350 miles over north pole

4: Callisto fly-by Dec. 12, 1997 at 1,300 miles

5: Europa fly-by Jan. 23, 1997 at 1,100, followed by Ganymede fly-by Feb. 28, 1997 at 1,300 miles

6: Europa fly-by April 22, 1997 at 300 miles, and again on May 31, 1997 at 220 miles (sixth and seventh orbits)

7: Exploration of Jupiter's magnetotail on 11th orbit, after Ganymede fly-by Oct. 5, 1997 at 380 miles

Source: NASA.

Galileo's probable mission scenario. As the mission gets under way, scientists will refine the series of fly-bys the Galileo spacecraft will make of Jupiter's four Galilean satellites—Io, Europa, Ganymede, and Callisto. After entering the Jupiter system from the asteroid belt, the orbiter will makes its only close fly-by of Io, and then proceed through the series of fly-bys shown. The last, 11th orbit (7), will swing the orbiter through Jupiter's enormous magnetosphere.

replacement of the vidicon cameras with a charge coupled device. These improved electronics will allow the imaging system to take photographs with a shortened exposure time: Instead of taking one picture per minute, as Voyager did, Galileo will take an image every two and one-third seconds. This reduces the effects of smear on close targets which the spacecraft is passing at rapid speed, and will allow scientists to "machine-gun" the images and combine them into moving pictures.

A second primary scientific objective of the Galileo mission is to observe and probe the active and turbulent atmosphere of this giant gas planet. Both the orbiter and probe will be called into service for these studies.

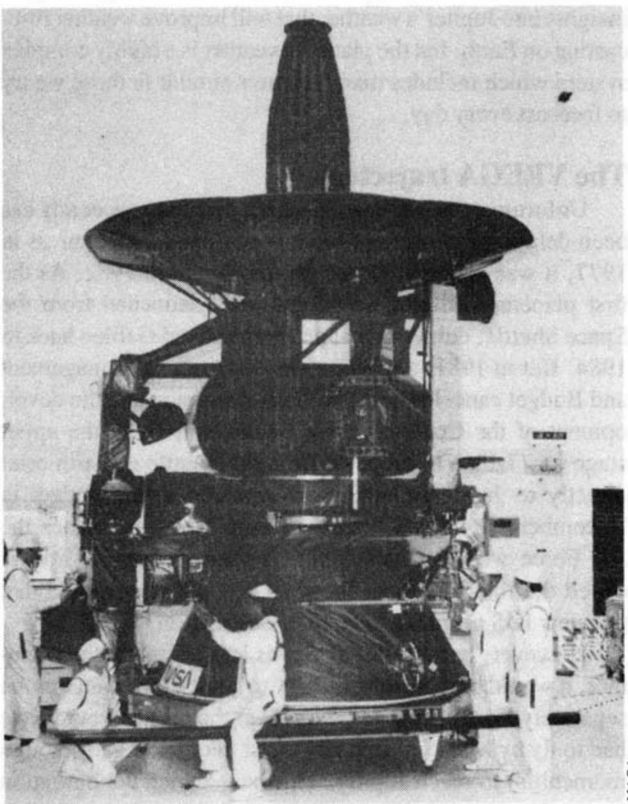
Storms and weather

Like the Earth, but on a far more massive scale, the atmosphere of Jupiter has clouds, storms, lightning, and winds at 200 miles per hour. The storm we know as the Great Red Spot, for example, is the size of three Earths. It is located at about 20° south latitude, and is an anticyclonic storm, rotating counterclockwise. It has been observed from Earth for hundreds of years.

Jupiter's atmosphere is made up of 89% hydrogen, and nearly the rest is helium, although there are traces of other gases. The overall atmospheric composition is obscured by clouds and a high-altitude "smog" which has hidden the atmosphere's deeper structure from Voyager's cameras. There are indications that the top-most cloud layer is made up of ammonia, but scientists believe there may be water clouds underneath.

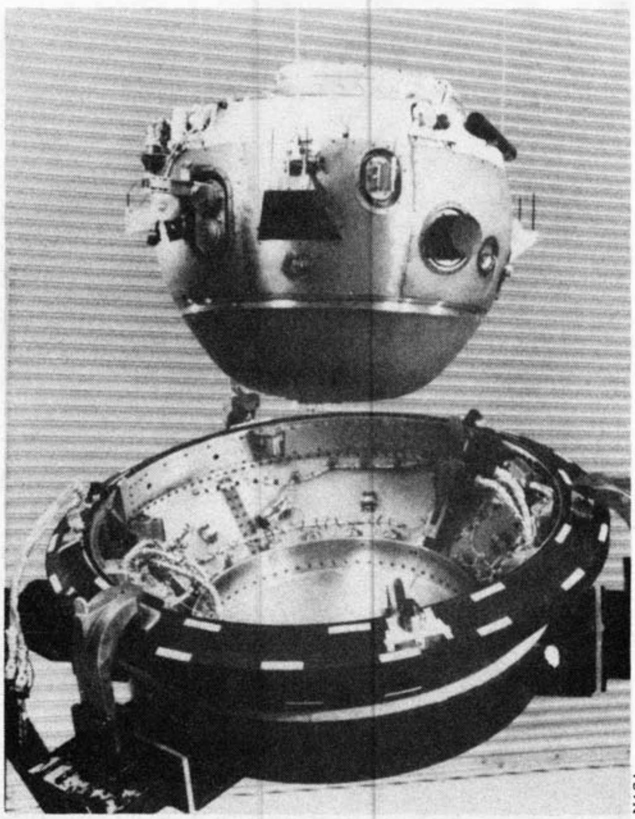
In addition to the dramatic Red Spot, Jupiter has white ovals, brown areas, and white plumes in its clouds. No one has come up yet with a satisfactory explanation of the beautiful colors in the atmosphere. This planet, whose diameter is ten times greater than Earth's, spins on its axis two and a half times faster than our planet does. This rapid rotation creates horizontal winds that produce shears between different layers and lead to the eddies in the clouds visible in the Voyager pictures. Voyager observed lightning at Jupiter, which would indicate that there are vertical instabilities in deeper levels of the atmosphere.

A probe will be sent through the atmosphere in order



NASA

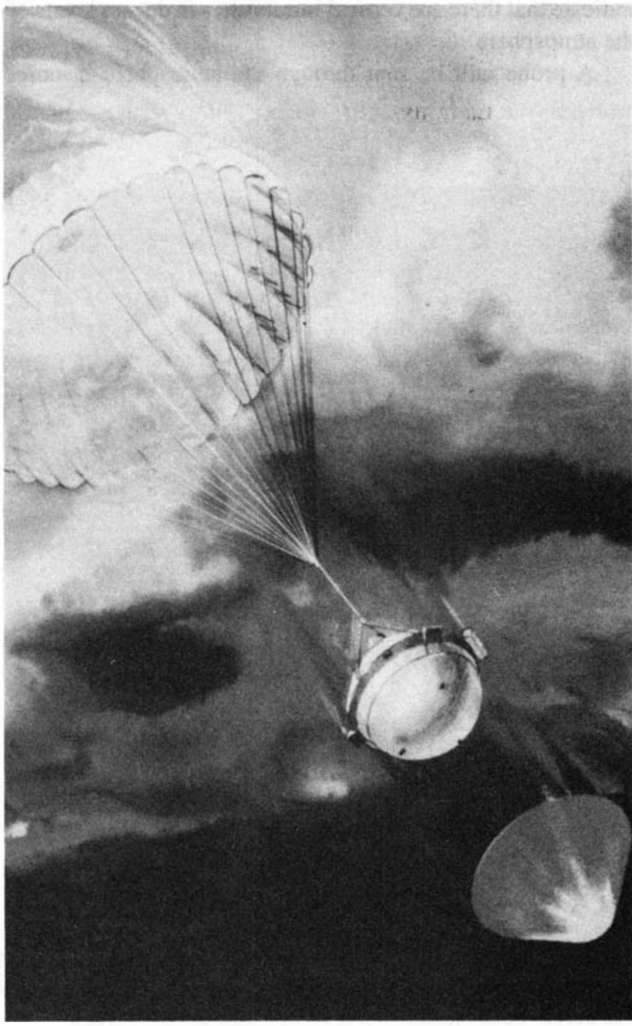
The Galileo spacecraft, being checked out at the Kennedy Space Center, before being mated with its Inertial Upper Stage (IUS) and placed in the payload bay of Atlantis. At the top the high-gain antenna, which communicates with Earth, is furled to protect it from the Sun. The probe is located at the bottom of the orbiter.



NASA

The deceleration module (lower section) and descent module which will enter Jupiter's atmosphere. The 750-pound probe was built by the Hughes Aircraft Company, under the management of NASA's Ames Research Center. It will separate from the orbiter 150 days before arrival at Jupiter.

to peer through the top-most cloud cover. After the probe separates from the Galileo orbiter, it will fly directly toward its Jupiter entry point at 6.5° north latitude. The probe has no propulsion or maneuvering capability of its own, and therefore must be sent on a precise course. As the probe approaches the giant planet, it will be traveling more than 100,000 miles per hour—a speed that would get you from New York to California in one and a half minutes. As the probe decelerates in contact with the upper layers of the atmosphere, an outer covering shell and heat shield will protect it and its scientific instruments from the tremendous heat of the entry. When its speed drops below the speed of sound, which should take about two minutes, the deceleration module will be jettisoned, and the little, 2½ foot-diameter probe, carrying 66 pounds of scientific instruments, will descend through Jupiter's atmosphere beneath an 8-foot parachute. It will enter the atmosphere at less than 1 bar of pressure, roughly the same as the pressure at sea level on Earth. The pressure will increase with the descent, and scientists hope the probe will be able to send back data on the clouds, their composition, lightning, and other features of the atmosphere for up to 75 minutes, at which time the pressure may rise to 25 bars, 125 miles below its entry altitude.



This artist's depiction shows the separation of the protective nose cone (bottom) from the probe as it descends through Jupiter's atmosphere. The probe will enter the sunlit side of Jupiter, but be in darkness for the end of its journey.

As the probe descends, it will be carefully tracked from the orbiter, 133,000 miles overhead, which will relay its data to Earth. It will travel down with the winds, which will give scientists a picture of wind speeds and direction in various layers of the atmosphere.

One of the six instruments on the probe, called a nephelometer, sends out short flashes of coherent laser light and measures the returned signals from nearby clouds. Measurements taken in the near infrared will obtain images through "windows" or breaks in the clouds, and can discern if there is methane and other material in the cloud formations. The probe will measure the pressure, temperature, cloud formation, and atmospheric composition of different layers of the atmosphere. By taking measurements in a number of different wavelengths, it will help provide a three dimensional map of the whirling, stormy atmosphere of Jupiter.

Scientists cannot say now whether or not they will gain insights into Jupiter's weather that will improve weather forecasting on Earth, but the planet's weather is a highly complex system which includes many features similar to those we try to forecast every day.

The VEEGA trajectory

Unfortunately, the launch of the Galileo spacecraft has been delayed a number of times—approved by Congress in 1977, it was originally to be Jupiter-bound in 1982. As the first planetary mission scheduled to be launched from the Space Shuttle, delays in that program moved Galileo back to 1984. But in 1981, the White House Office of Management and Budget canceled both the Galileo mission and the development of the Centaur rocket, which was to be the upper stage for Galileo to propel it from the Shuttle in Earth orbit directly to Jupiter. Galileo was restored to the budget in December of that year, but the Centaur was not. Since the Air Force was then developing a three-stage solid rocket called the Interim Upper Stage (IUS), it was proposed that this new IUS propel Galileo to its destination.

However, because the IUS was less energetic than Centaur, it would have been necessary to launch the Jupiter probe separately from the orbiter. Moreover the orbiter would have had to fly by Mars for a gravity assist in order to gain enough momentum to reach Jupiter. This new launch configuration would have required significant redesign of the Galileo spacecraft, and the National Aeronautics and Space Administration (NASA) was able to win approval to go ahead with the Centaur, when the Air Force began having serious problems developing the Interim Upper Stage.

In January 1982, however, NASA terminated the Centaur program due to budgetary considerations, and Galileo was back on another solid rocket also called the IUS, but now standing for "Inertial Upper Stage" consisting of only two stages. Later that year, the Congress legislated reinstatement of the Centaur program, and set the launch of Galileo for May 1986, aboard the Shuttle.

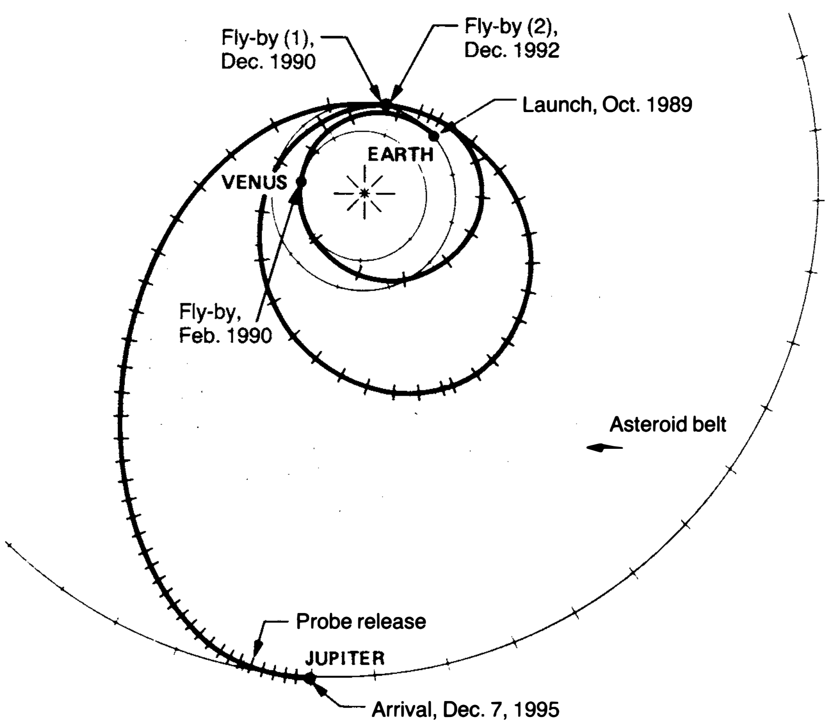
Less than four months before Galileo was to finally begin its trip to Jupiter, the Challenger was lost. Fear that the liquid hydrogen fuel that Centaur was carrying was too dangerous to be on a manned spacecraft led to the cancelation, once again, of the Centaur for use on the Shuttle. Galileo will be launched from Atlantis by an IUS. Galileo, however, will not go *directly* to Jupiter, because of the less favorable alignment of the planets and the reduced power available from the IUS.

Figure 2 shows what route Galileo will take to arrive at Jupiter in December of 1995. Three gravity assists will be needed, the first at Venus, and then two back near the Earth. VEEGA stands for Venus-Earth-Earth-Gravity-Assist. Galileo will reach Venus before the Magellan spacecraft, which was launched last May from the Shuttle, and will take a look at this shrouded planet with a different set of instruments than the radar on Magellan.

Galileo was originally designed to go from the Earth *away* from the Sun, not toward it, and operate where sunlight is 25 times weaker than at Earth. Therefore, precautions have been taken to protect its sensitive instruments from damage from the increased heat at Venus. Engineers designed a set of sunshades to protect the craft, and for this system to work, the front end of Galileo must be aimed precisely at the Sun. The main antenna will remain furled for protection until after the first Earth fly-by in December 1990. This means that at Venus, the data will be recorded for playback to waiting scientists via the low-gain antenna when the spacecraft is close to Earth, rather than being sent in real time. At Venus, Galileo will observe the planet in the infrared and the ultraviolet, which will help in the search for cloud patterns and, possibly, for lightning storms. The radar instrument on the Magellan craft will be looking through the clouds to the surface features of the planet.

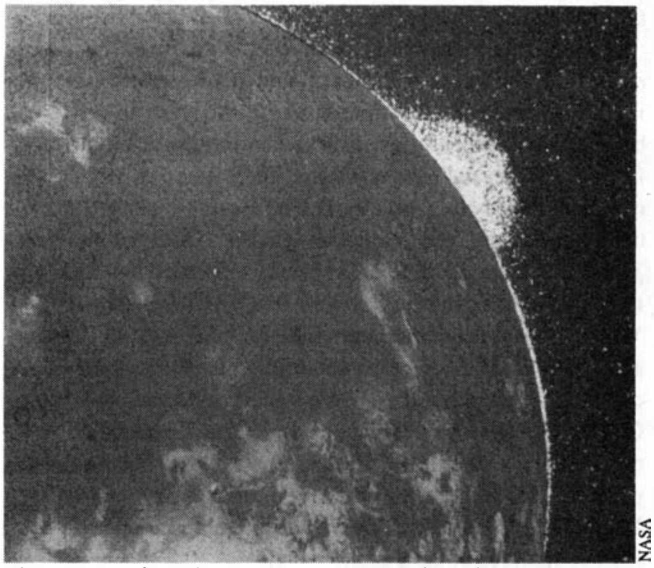
About 14 months after launch, Galileo will approach Earth from the nightside and observe both the dark and bright sides of the Moon, and then it will unfurl its high-gain antenna after the Earth fly-by. Galileo, with its sophisticated instruments, will look at the Moon for the first time since the

FIGURE 2
Galileo's VEEGA trajectory to Jupiter

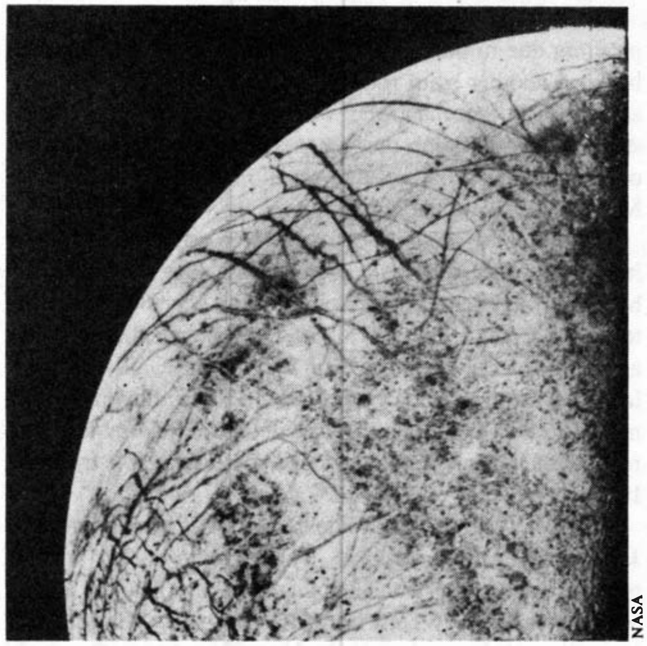


Three gravity assist maneuvers will be needed to get the Galileo spacecraft to Jupiter, because of Jupiter's alignment with Earth, and because of the reduced available power from the Inertial Upper Stage that will boost Galileo into space from the Space Shuttle. VEEGA is an acronym for Venus-Earth-Earth Gravity Assist: Galileo will arrive at Venus in February 1990, fly by Earth in December 1990, and fly by Earth again in December 1992. The spacecraft will finally arrive at Jupiter in early December 1995.

Source: NASA.

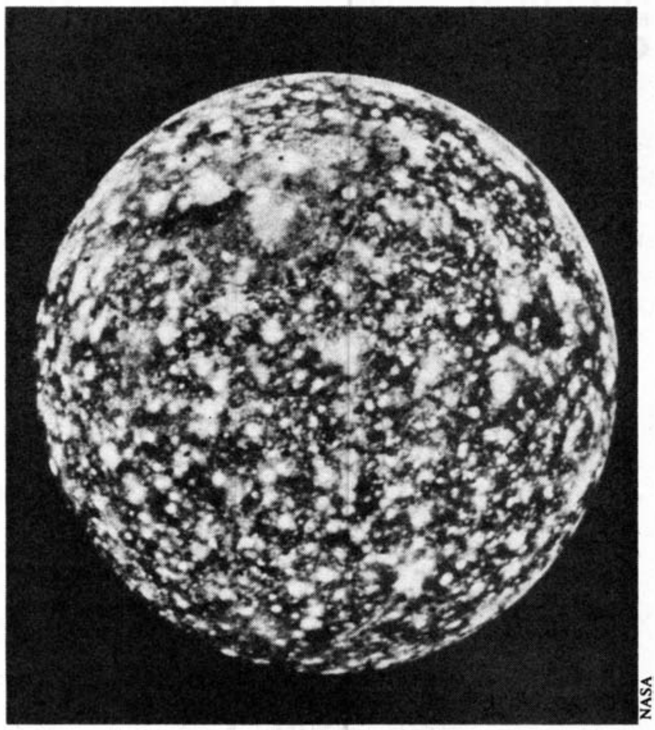


The moon Io: One of Voyager's most astonishing discoveries was the existence of erupting volcanoes on this moon. In this enhanced photo, taken from nearly a half-million miles, a volcanic plume rising from the limb of the moon is clearly visible. Eight erupting volcanoes were seen by Voyager 1.

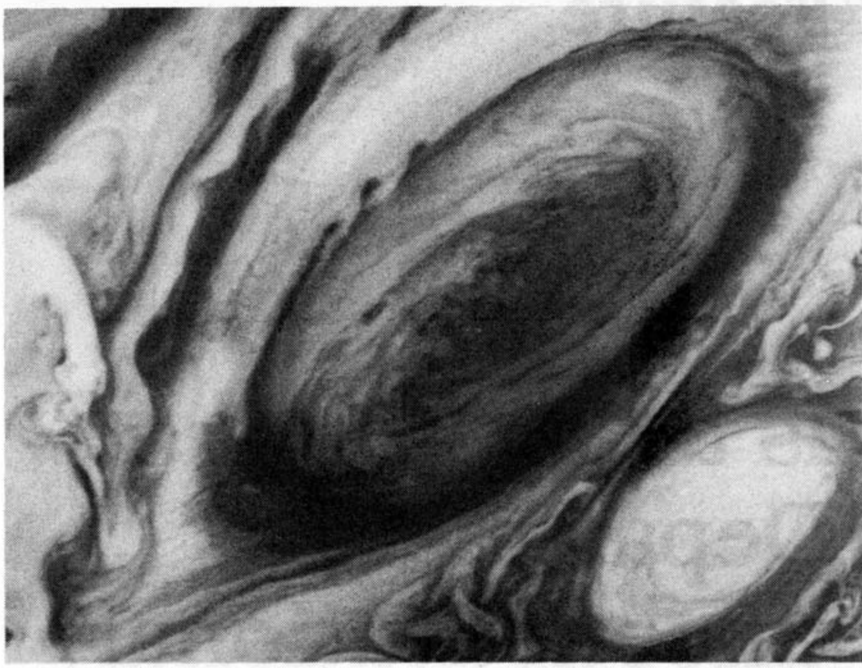


The Galilean moon Europa is covered with complicated linear features, which appear to be fracture lines. No large craters have been observed on Europa's surface, and therefore scientists believe it may be a thin ice crust, which is resurfaced by eruptions of water from underneath.

The moon Ganymede appears to have a combination of young and old terrain. The regions with numerous impact craters, seen here in the lower right of the photo are the older features. The grooved terrain (bottom) is a younger surface, still being reshaped by geologic activity.



Callisto, the farthest Galilean satellite, is clearly the coldest and least geologically active. It is covered with a beautiful array of craters, some with bright spots which may expose fresh ice and frost. This photograph of Callisto was taken by Voyager 1 from a distance of 675,000 miles.



Jupiter's Great Red Spot is one of the most "observed" features in the Solar System. This mosaic from Voyager 1, clearly shows the swirling storm in the center of the Spot. Scientists have observed that the structure of the large white spot (bottom right) is identical to that of the Great Red Spot. Both are anticyclonic (rotating counterclockwise in the southern hemisphere), also indicating their meteorological similarity.

end of the Apollo program, 15 years ago. The spacecraft will look over the poles of the Moon, which have never been imaged before. Some scientists believe there may be water at the lunar poles, though this is quite unlikely. As it turns out, Galileo will help lay the basis for future lunar orbiters and for man's return to the Moon.

Eleven months after its first Earth passage, which will give Galileo enough energy to intersect the asteroid belt past Mars, it will encounter its first asteroid. Gaspra is believed to be a fairly representative mainbelt asteroid, about 10 miles across, and probably similar in composition to stony meteorites. Galileo will pass within about 600 miles of the asteroid at a relative speed of about 18,000 miles per hour, and will collect several pictures of Gaspra, and take measurements of its chemical composition and physical properties.

Thirteen months later, in December 1992, Galileo will have completed its two-year elliptical orbit around the Sun and will arrive back at Earth. As it will need a much larger ellipse, with a period of six years, in order to intersect the Jupiter's orbit, the second Earth fly-by is needed to "pump up" the spacecraft. Galileo will pass about 185 miles above the Earth's surface, gaining about 8,000 miles per hour in speed and changing its flight direction to finally set it toward its ultimate goal. Nine months later, on its second trip in the asteroid belt, Galileo may have an encounter with the asteroid Ida.

By the time the orbiter and probe reach Jupiter, they will have traveled about 2.5 billion miles in a complex path of ever-increasing ellipses, for more than six years. Undoubtedly still in perfect shape, the Galileo orbiter 22-month-long Jupiter mission will begin.

At the end of its planetary observations and satellite encounters, Galileo will swing around the planet in a wide ellipse to plow through Jupiter's magnetotail. This enormous structure is the largest single object in the Solar System—certainly one of the most interesting aspects of the Jupiter system.

On Earth, the solar wind provides the particles and energy for the magnetosphere and the Van Allen radiation belts circling our planet. On Jupiter, however, it is the planet's own strong magnetic field and rapid rate of rotation that appears to power the magnetosphere. Between 3 and 11 Jupiter-radii—between 132,600 and 486,000 miles—from the planet, is a torus of dense plasma, which was found by the Pioneer spacecraft.

Voyager revealed that sulfur and sulfur dioxide ions are present in this plasma, which scientists assume comes from volcanic eruptions on Io. The interaction between Jupiter, its moons, radiation belts, and magnetosphere will be the final observations Galileo will make of the Jupiter system.

NASA managers and the Galileo scientists are hoping that the technology and hardware developed for Galileo will be brought into service for future outer-planetary orbiter-probe missions. The Cassini mission to Saturn has been proposed, where a probe would descend into the thick atmosphere of the moon, Titan.

These *in situ* studies of the outer planets, complemented by continuing detailed observation of our nearer neighbors the Moon, Venus, and Mars are opening the second great age of planetary space science, following the remarkable discoveries of the Pioneers and Voyagers.