Galileo Mission to Jupiter
Educator's Slide Set Vol. 1

August 1995

Launched on October 18, 1989, Galileo has used planetary gravity assists to put itself on a trajectory to Jupiter. This technique allows the spacecraft to change velocity as it passes close by a planet. Galileo's six-year path to Jupiter took it past Venus once and Earth twice, with two passes through the asteroid belt that provided flybys of Gaspra and Ida.

The Galileo spacecraft consists of two principal parts: an orbiter and an atmospheric probe. The probe was released from the orbiter 148 days before arrival at Jupiter and will enter Jupiter's atmosphere to study the temperature, pressure and composition of the cloud layers and relay its data back to the orbiter. After completion of the probe mission, the orbiter will perform an orbital mission about Jupiter doing ten close flybys of the Galilean satellites Europa, Ganymede, and Callisto, one each on ten of eleven orbits during the 2-year orbital mission. Io, the other Galilean satellite, will be visited with a close flyby just prior to the probe entry into Jupiter. Galileo will also study Jupiter's atmosphere and magnetosphere during each of its orbits around Jupiter. Galileo arrives at Jupiter on December 7, 1995.

Short Captions

1. Launch of Galileo on STS-34 Atlantis

Liftoff of STS-34 Atlantis, carrying the Galileo spacecraft and its Inertial Upper Stage (IUS) booster on October 18, 1989 at 12:53 p.m. EDT. P-35036BC

Extended Descriptions

The shuttle mission was commanded by Donald E. Williams and piloted by Michael J. McCulley. Mission specialists were Shannon W. Lucid, Franklin W. Chang-Diaz, and Ellen S. Baker.

NASA policy in the early 1980's was to launch all spacecraft from the shuttle, unlike earlier, expendable-rocket-launched interplanetary missions such as Voyager (which visited Jupiter, Saturn, Uranus and Neptune).

Initially, it seemed as though Galileo's launch was fated to be delayed. Worries over whether Hurricane Hugo would come onshore at the Kennedy Space Center mounted until, at the last moment, the destructive force of the storm swept north of the launch site, allowing engineers to relax. Then, the day before the rescheduled launch, a 7.1 earthquake, centered just 25 kilometers (15 miles) south of Sunnyvale, California, caused evacuation of the Inertial Upper Stage control center there, which was crucial to mission operations. The control center crew recovered as the night progressed, allowing the countdown to continue.

Rocket Power

It wasn't a trivial matter to get Atlantis and its launch vehicle— 2,056,277 kilograms (4,523,810 pounds) at launch—into orbit. Each of the three main engines in tail of the shuttle can provide almost a half-million pounds of thrust. The thrust to weight ratio for these engines (about 70:1) is the best in the world— each engine weighs less than 3,200 kilograms (7,000 pounds) but puts out the power equivalent of seven Hoover Dams! The shuttle experiences a maximum of 3 g's of gravity (that is, three times the gravitational force that we feel here on Earth) during ascent; due to vibration, loads on parts of the spacecraft may exceed 10 g's.

Since the shuttle needs to have a daylight landing opportunity at the trans-Atlantic landing abort sites, and since there are performance constraints on Galileo's inertial upper stage, spacecraft liftoff could only occur during certain periods of time. The launch opportunity opened on Oct. 12, 1989 for a 10-minute period. The launch window then grew each day, reaching a maximum of 47 minutes on Nov. 2. The window then decreased each day through the remainder of the launch opportunity, which ended on November 21, 1995.

Aiming at Jupiter

To get to Jupiter, Galileo had to be inserted into its interplanetary trajectory at the correct time so that, when it arrives at Jupiter's orbit, Jupiter is right there (and not, say, half an orbit away!). This task might be compared to throwing a water balloon at someone running in front of you. You have to lead the aim point by just the right amount to hit the target; if you aim at where the person is right when you throw the balloon, you'll end up missing the target. If an interplanetary spacecraft misses its launch opportunity, we have to wait for the orbital motion of the planets to realign them into the "correct" geometry for a successful launch opportunity.

Because Galileo used a VEEGA (for Venus-Earth-Earth Gravity Assist) trajectory to fly to Jupiter (rather than a direct trajectory), its launch opportunities did not repeat at regular intervals the way direct trajectories do. This is because there are many ways to combine a launch from Earth with one Venus and two Earth flybys to get to Jupiter. The next three VEEGA opportunities to Jupiter after the one Galileo used occurred in November 1989 and May/June 1991. There were actually two different opportunities in the May/June 1991 time period.

2. Deployment of Galileo and the IUS

Deployment of Galileo and the IUS from the cargo bay of STS-34 Atlantis at 7:15 p.m. EDT on October 18, 1989. P-35213

Mission Specialist Shannon Lucid started Galileo's deployment by pushing a button; automatic systems then took over to separate Galileo from the shuttle. As deployment finished Commander Donald E. Williams declared "Galileo is on its way to another world. It's in the hands of the best flight controllers in this world—fly safely."

Beginning an hour after deployment, two rocket stages of Galileo's IUS booster fired one after the other. Galileo separated from the IUS's second stage at 9:05 p.m. and began its flight to Venus for the first of three gravity assisted flybys, which would take Galileo to Jupiter.

Galileo was the second spacecraft to be launched using the IUS (Magellan ,the Venus radar mapping mission, was the first. Interestingly, even though Magellan was launched first (in April of 1989), Galileo reached Venus first.). Built by Boeing for the Air Force, the IUS, which uses solid (as opposed to liquid) fuel, gave Galileo an additional speed of 4.0 kilometers per second (8,640 miles per hour).

Gravity Assists

Why bother flying by Venus and Earth when the idea is to get to Jupiter? Because when Galileo flew by a planet, it was also picking up a "gravity assist."

"Gravity assist" is a technique in which a miniscule fraction of a planet's orbital energy is transferred to a spacecraft, bending its path around the planet and increasing its speed around the Sun, rather like a slingshot or a game of cosmic billiards. Several such maneuvers are necessary to enable Galileo to get to Jupiter. The first gravity assist occurred at Venus on February 10, 1990. Two additional gravity assists from flybys of Earth (on December 8, 1990 and December 8, 1992) also helped to send Galileo on its way. Without the boost provided by these flybys, Galileo would need an extra 10,900 kilograms (23,980 pounds) of propellant—about twelve times more than was on board at launch.

Close flybys and gravity assists utilizing Jupiter's moons will also be used to enable Galileo to make a complex tour of Jupiter's system. An additional 3,600 kilograms (7,920 pounds) of propellant (about four times the total amount of propellant on the spacecraft at launch) would be needed to fly the tour without the billiards-like gravity assist technique.

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3. Infrared Image of low clouds on Venus

False-color infrared image of low clouds on Venus' night side, taken on February 10, 1990. Range 96,600 kilometers (60,000 miles) above the planet. P-37539

Venus is shrouded in thick sulfuric acid clouds many kilometers thick, so using a standard camera in visible light to take pictures of the planet results in a bland-looking ball. In this image, Galileo used its Near Infrared Mapping Spectrometer (NIMS) as the spacecraft approached the planet's night side. Bright slivers of sunlit high clouds are visible on the limb (or planet "edges") at top and bottom. The image was constructed using an infrared wavelength of 2.3 microns (90 millionths of an inch), which is about three times longer than the longest wavelength of light visible to the human eye.

The map shows the turbulent, cloudy middle atmosphere some 50 to 55 kilometers (30 to 34 miles) above the Venusian surface; these clouds are 10 to 16 kilometers (6 to 10 miles) below the visible cloud tops. The red color represents the radiant heat from the lower atmosphere (about 400 degrees Fahrenheit) shining through the sulfuric acid clouds, which appear as much as 10 times darker than the bright gaps between clouds. This cloud layer is about –30 degrees Fahrenheit, at a pressure about one half Earth's surface atmospheric pressure.

Near the equator, the clouds appear fluffy and blocky; further north, they are stretched out into east-west filaments by winds estimated at more than 70 meters per second (150 miles per hour). At this height above the surface, the poles are capped by thick clouds.

What is False Color?

Astronomers often observe planets, stars, and other objects in light wavelengths that are invisible to the human eye, such as infrared (wavelengths slightly longer than red light) or ultraviolet (slightly shorter than violet light). But, how do you show a human a picture taken in "invisible" light? Scientists assign different colors to different wavelengths, giving a false sense of color to the image. This technique allows them to easily see patterns and detail that would otherwise be hidden.

False color can also be used to enhance detail in regular pictures where there isn't a wide range of color—for example, in an aerial photo of a jungle, which may appear as a carpet of unbroken green. By assigning slightly different shades of visible green to radically different false colors like red and blue, scientists can make detail stand out. Or, the faint colors of a planetary picture can be boosted brighter, making it easier to pick out geological features. Such image processing techniques are also used in areas such as CAT scans.

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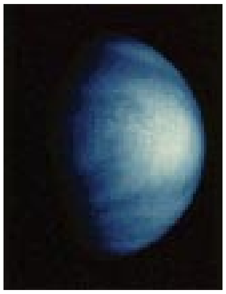
4. Venus

Colorized picture of Venus through a violet filter. Only the uppermost clouds (about 60-70 kilometers (36–42 miles) above the surface) are visible at this wavelength. P-37218

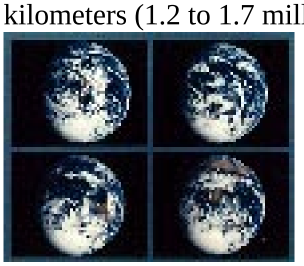


This picture of Venus was (appropriately, for a planet named for the goddess of Love) taken on February 14, 1990, from a distance of almost 2.84 million kilometers (1.7 million miles), about 6 days after Galileo's closest approach to the planet. The image has been colorized to a bluish hue to emphasize subtle contrasts in the cloud marking and to indicate that it was taken through a violet filter. Features in the sulfuric acid clouds near the top of the planet's atmosphere are most prominent in violet and ultraviolet light. This image shows the general trend of cloud bands that stretch along the east-west direction (North is at the top, and the evening terminator is on the left, so East is to the left), and the brighter polar "hoods," features that had been seen in previous Venus observations. All of these features are embedded in winds that flow from east to west at a speed of about 380 kilometers per hour (230 miles per hour). The smallest features visible are about 75 kilometers (45 miles) across.

The bright white-colored region on the planet's right side is the "subsolar point," where the sun shines down directly on the planet's surface (i.e. if you were standing at that point on Venus, the Sun would be directly overhead, and your watch, calibrated to Venusian time, would tell you that it was 12 noon). Note the dark spider-shaped pattern that is just to the left of the area; scientists still are unsure as to the exact nature of this pattern, though one possibility is that it's a storm system.

5. Images of Earth

Global images of Earth from Galileo. In each frame, the continent of Antarctica is visible at the bottom of the globe. South America may be seen in the first frame (top left), the great Pacific Ocean in the second (bottom left), India at the top and Australia to the right in the third (top right), and Africa in the fourth (bottom right). Taken at six-hour intervals on December 11, 1990, at a range of between 2 and 2.7 million kilometers (1.2 to 1.7 million miles). P-37630



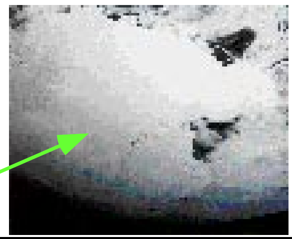
These images were taken during Galileo's first Earth flyby. This gravity assist increased Galileo's speed around the Sun by about 5.2 kilometers per second (or 11,600 miles per hour) and substantially redirected Galileo as required for its flybys of the asteroid Gaspra in October 1991 and Earth in 1992. Galileo's closest approach (960 kilometers, or 597 miles, above the Earth's surface) to the Earth was on December 8, 1990, 3 days before these pictures were taken.

Each of these images is a color composite, made up using images taken through red, green, and violet filters. The four images are part of the Galileo Earth spin movie, a 256-frame time-lapse motion picture that shows a 25-hour period of Earth's rotation and atmospheric dynamics.

6. Antarctica

This mosaic of the vast Antarctic continent shows the Ross Ice Shelf and its sharp border with the dark waters of the Ross Sea, merging into the South Pacific Ocean. The Transantarctic mountain range can be seen downward and to the left of the Ross Ice Shelf. December 8, 1990. Range, 200,000 kilometers (124,300 miles). P-37593

General location of South Pole



This picture was "mosaic-ed" together out of 40 different images that were taken several hours after Galileo's closest approach to the Earth.

You can see three different oceans (through breaks in the clouds) in this picture: the Pacific to the lower right, the Indian to the upper right, and a small section of the Atlantic at the upper left. Nearly the entire continent was sunlit at the time, just two weeks before Antarctic midsummer. The South Pole is left of center; the arc of dark spots extending below there and to the right is the Transantarctic Mountain Range. To the right of the mountains is the vast Ross Ice Shelf and its sharp border with the dark waters of the Ross Sea, merging into the South Pacific. The faint blue line along the curved limb of Earth, at the bottom, marks our planet's atmosphere.

Up and Down in Space

We've oriented this Antarctica image using the familiar North-at-the-top reference, but some people find it disconcerting to look at this orientation; it feels like you might fall off of the bottom of the planet! You might want to try turning the picture "upside down," as well. Similarly, try changing your point of view for any of the images in this collection—in outer space, there is no up or down!

The Land of the Midnight Sun

Unless you live right on top of the equator, you're used to finding that days in winter are far shorter than are days in summer. At the north and south pole, the tilt of the Earth's rotation axis to the plane of the planet's orbit about the Sun means that summer brings 24-hour days (but winter brings 24 hour nights). Using a globe that's appropriately tilted (about 23 degrees), turn out the lights and set up a "Sun" (e.g. a flashlight). Can you replicate the lighting conditions seen in the picture above? Does this correspond with it being "Summer" in the Southern Hemisphere?

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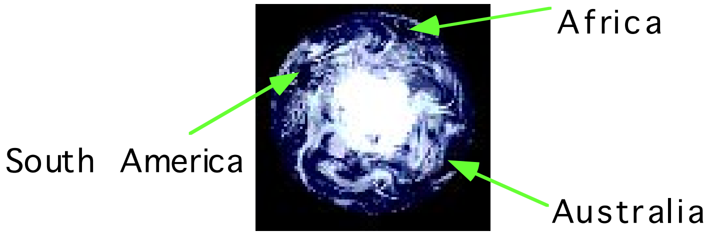
7. South Polar Projection of Earth

This view of the Earth shows a wonderfully unique but physically impossible view of the southern hemisphere and Antarctica. While a spacecraft could find itself directly over the Earth's pole, roughly half of the image should be in darkness! This view was created by mosaicing together several images taken by Galileo over a 24 hour period and projecting them as they would be seen from above the pole. The continents of South America, Africa, and Australia are respectively seen at the middle left, upper right, and lower right. The slightly bluish ice and snow of Antarctica include large ice shelves (upper left, lower middle), a broad fan of broken offshore pack ice (lower left and middle) and continental glaciers protruding into the sea (lower right). The regularly spaced weather systems are prominent. December 1990 P-42501AC

Most spacecraft travelling near the Earth's poles are in very low Earth orbit, and cannot acquire panoramic shots like this one. Galileo's view of the southern hemisphere, combined with the spacecraft's special spectral properties (four separate narrowband filters that measure the brightness of reflected light at specific infrared wavelengths), led to a number of unique observations. For example, Galileo's cameras distinguished between ice and high stratospheric clouds, allowing scientists to study the correlation between these clouds and growth of the ozone hole.



Galileo and Earth Observations

Although there are many different satellites in Earth orbit monitoring ground and atmospheric conditions, Galileo's pictures provided a unique look at our planet. Galileo can discriminate between water vapor and condensed water in clouds, pick out diagnostics of the state of health of plant life, and pinpoint regional differences in land use policy.

Galileo's pictures are also a preview for future remote-sensing systems like the Earth Observing System , which will make global surveys at high spectral resolution, albeit from low Earth orbit.

8. Western Hemisphere of Moon

This image of the western hemisphere of the Moon shows the Orientale Basin (600 miles in diameter) in the center. It was computer processed to enhance the visibility of small features. December 9, 1990 at 9:35 a.m. PST. Range, 563,000 kilometers (350,000 miles). P-37327

Here's a view of the Moon that can't be seen from the Earth, showing parts of both the "near" and "far" sides of the Moon! (only one side of the Moon points towards the Earth) This image was taken through a green filter.

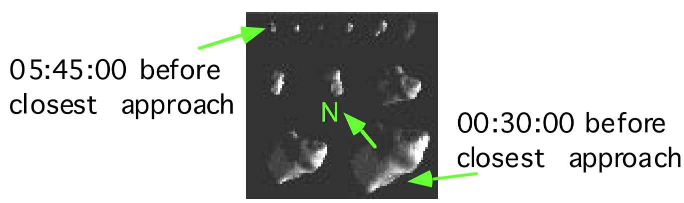
The Orientale Basin was formed about 3.8 billion years ago by the impact of an asteroid-sized body. Orientale's dark center is a small mare. To the right is the near side of the Moon that faces the Earth, with the great, dark Oceanus Procellarum above and the small, circular, dark Mare Humorum below. Maria (from the Latin "mare," or "sea") are broad plains formed mostly over 3 billion years ago as vast basaltic lava flows. To the left is the lunar far side (which is not visible from Earth) with fewer maria. At the lower left is the South-Pole-Aitken basin, the largest, deepest impact basin yet discovered in the Solar system. The basin is 2500 kilometers (1500 miles) in diameter, which resembles Orientale but is larger, much older and more weathered and battered by cratering. The intervening cratered highlands of both sides, as well as the maria, are dotted with bright, young craters. This image was "reprojected" so that the Orientale Basin is centered.

9. Gaspra rotation sequence

This montage of 11 images shows Gaspra growing progressively larger in the field of view of Galileo's camera. Asteroid Gaspra rotates once in 7 hours, 3 minutes and counterclockwise when viewed from above the north pole— these images cover almost one Gaspra "day." Many craters are visible on the surface of Gaspra. The earliest view (upper left) was taken 5 3/4 hours before closest approach from a range of 164,000 kilometers (102,000 miles). P-41383

Galileo's flyby of the asteroid Gaspra marked the first ever spacecraft encounter with an asteroid. The last view (lower right) was taken at a range of 16,000 kilometers (10,000 miles), 30 minutes before closest approach.

Gaspra spins counterclockwise; its north pole is to the upper left, and the "nose" which points upward in the first image, is seen rotating back into shadow, emerging at lower left, and rotating to upper right.



What did we know about Gaspra Before Galileo's Flyby?

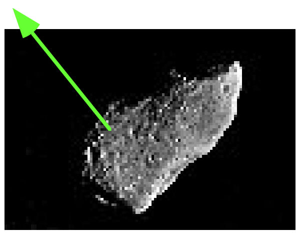
From ground-based observations, quite a bit of information was known about Gaspra *before* the encounter. Discovered in 1916 by astronomer Grigori Neujmin at Simeis Observatory in the Ukraine, Gaspra was named for a scientists' resort on the Crimean Peninsula. Gaspra, an S-type (or stony) asteroid, is believed to be made up of metallic and rocky minerals including iron, nickel, olivine, and pyroxene. This asteroid is just one of more than 15,000 asteroids comprising the "main belt"—a large doughnut- shaped region midway between Mars and Jupiter. Gaspra is located about 331 million kilometers (206 million miles) from the Sun, near the inner edge of the main belt. Asteroids are also known as minor planets; many are much larger than Gaspra, ranging up to more than 1000 kilometers (600 miles) in diameter.

Investigating asteroids like Gaspra and Ida is important to scientists because asteroids contain important clues to processes in the early solar system. Asteroids are believed to have formed during the earliest stages of the solar system and thus are primitive bodies that could provide key information about the evolution of the Sun and its planets. Asteroids were formed when the other planets were formed in the early solar nebula. In addition, encountering Gaspra helped to calibrate ground-based observations. Since all previous observations of asteroids have been limited to ground-based viewing, Galileo's encounter provided a unique opportunity to increase our knowledge and update our models about how asteroids form and evolve. For that matter, since meteorites are believed to be chunks of asteroids, categorizing the composition of asteroids may allow scientists to correlate meteorites with their parent asteroids.

10. Highest-Resolution Image of Gaspra

Highest resolution picture of asteroid 951 Gaspra. Gaspra is an irregular body with dimensions about 19 x 12 x 11 kilometers (12 x 7.5 x 7 miles). The north pole is located at upper left. The sun is shining from the right; phase angle (the angle between the sun, Gaspra, and the observer; a phase angle of 0 degrees means the sun is behind you, and a phase angle of 180 degrees means the sun is behind the object you're looking at) is 50 degrees. A striking feature is the abundance of small craters—more than 600 craters, 100-500 meters (330-1650 feet) in diameter are visible here. Note the "faceted" shape, indicating Gaspra had a violent collisional history. 10 minutes before closest approach on October 29, 1991. Range, 5,300 kilometers (3,300 miles). P-40449

North Pole



This picture of asteroid Gaspra is a mosaic of two images. The resolution, with features as small as 108 meters (354 feet) being, is the highest for the Gaspra encounter, and is about three times better than that seen in the previous slide. At closest approach, Galileo was just 1.5 seconds and 5 kilometers (3 miles) from the aim point--a bull's-eye in planetary distances. Dr. Michael Belton, Solid-State Imaging Experiment Team Leader, said, " It was like taking a picture of a large house in San Francisco from Los Angeles."

Because the asteroid is small, its surface gravitational force is two thousand times smaller than that of the Earth's, yielding an escape speed of only 10 meters per second (22 miles per hour); an Olympic-caliber sprinter could run himself into orbit! A 200 pound man would weigh 0.1 pounds!

In this view, we can see an illuminated portion of Gaspra that is about 18 kilometers (11 miles) long from lower left to upper right. The large inward bend along the asteroid's lower right edge is about 6 kilometers (3.7 miles) across, and the prominent crater on the center left edge is about 1.5 kilometers (1 mile) in diameter. Gaspra has far more small craters compared to larger ones than other, previously studied bodies of comparable size, such as the moons of Mars. This has implications for Gaspra's age (see "Cratering and Age Determination," below).

Even though several craters are visible on Gaspra, none approaches the scale of the asteroid's radius. Evidently, Gaspra lacks the large craters common on the surfaces of many planetary satellites. This is consistent with the theory that Gaspra is of comparatively recent origin from the collisional breakup of a larger body, a survivor of a series of catastrophic events. In fact, Gaspra's current size may be only a tenth of its parent's original size. The prominence of groove-like linear features, believed to be related to fractures, are consistent with such a history. These linear depressions, 100-300 meters (60-180 feet) wide and tens of meters (tens of yards) deep, are in two crossing groups with slightly different shapes, one group wider and more pitted than the other. Grooves had previously been seen only on Mars's moon Phobos, but were predicted for asteroids as well.

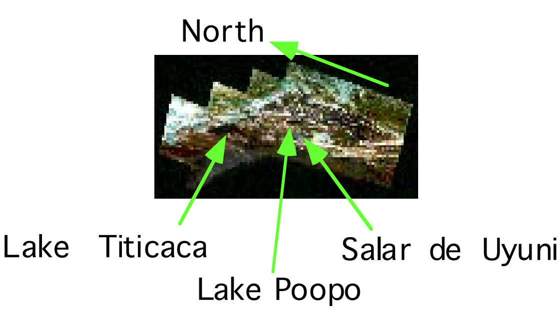
Cratering and Age Determination

Scientists can count craters on planets and asteroids as one way to tell the "age" of the surface. You can test this for yourself by gathering up a paintbrush, some paint, and a (large) piece of paper (alternatively, substitute water and a large solid-colored piece of cloth like a bedsheet for the paint and paper). Load the paintbrush up with paint, and then give it a few gentle shakes over the paper. Now, stop and count the number of "craters" on the paper. Repeat this exercise a few times (reloading the paintbrush each time; using different colors of paint each time is a nice artistic variation). You should notice several things: the "older" the planet surface (e.g. the more time that you allow the paper to be "cratered,"), the more "craters" present. The newer craters tend to overlay and even completely hide the older craters (this is easier to see when you use a different color of paint for each cratering episode,). And, there tend to be more small craters than large craters (since there are far more small asteroids and rocks that could hit another asteroid than there are large ones).

How does this apply to Gaspra? We expect that Gaspra should, eventually, have a collision with a relatively large rock or asteroid. Since we don't see any large craters on Gaspra that such a collision would leave behind, this probably means that Gaspra is relatively young, and simply hasn't picked up any major scars as yet (much like how we can tell that a car is new because it doesn't have any scratches or dents).

11. Central Andes of South America

This false-color mosaic of the central part of the Andes mountains of South America shows the area where Chile, Peru, and Bolivia meet. The Pacific Coast appears at the bottom of the image. Galileo captured this view as it traveled west over the Pacific Ocean, looking back at the Andes. Lakes Titicaca and Poopo are nearly black patches at left and center, respectively; a large light-blue area below and to the right of Lake Poopo is Salar de Uyuni, a dry salt lake. Light-blue patches in the mountains at top and left are glaciers. Range, 25,000 kilometers (15,500 miles). P-41493



Galileo said its third and final goodbye to the Earth on December 8, 1992, at 7:09 a.m. PST. The spacecraft swept within 303.1 kilometers (182 miles) of the South Atlantic Ocean, its point of closest approach to the Earth. This, the last of three planetary gravity assists, added 3.7 kilometers per second (7,992 miles per hour) to the spacecraft's speed in its solar orbit. In addition, the gravity assist changed the spacecraft's direction slightly, so its elliptical orbit will intersect the orbit of Jupiter on December 7, 1995, about 780 million kilometers (470 million miles) from the Sun. The navigation, as in previous gravity assists, was impeccable. Galileo was within a kilometer of its intended path, and was just 0.1 second early.

This false-color mosaic is made up of 42 different images. The combination of visible and near-infrared filters (green, 0.76 micron (30 millionths of an inch) and 1.0 micron (40 millionths of an inch)) was chosen for this picture to separate regions with distinct vegetation and soil types. North is to the left; for a sense of scale, consider that the dry salt lake Salar de Uyuni is some 120 kilometers (75 miles) across. These lakes lie in the Altiplano, a region between the western and eastern Andes, which are covered by clouds. The water/ice content of the clouds is indicated by their shade of pink (pinker shades indicate more water content). The vegetated Gran Chaco plains east of the Andes are pale green (top of picture). Images like these are a preview of future remote-sensing programs such as the Earth Observing System.

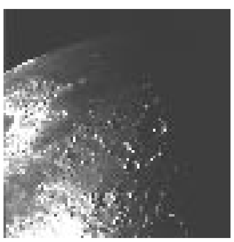
12. The Horn of Africa

Visible in this image of northeast Africa and the Arabian Peninsula are most of Egypt (left of center), including the Nile Valley, the Red Sea (slightly above center), Israel, and Jordan. In the center, below the coastal cloud, is Khartoum, at the confluence of the Blue Nile and the White Nile. Somalia (lower right) is partly covered by clouds. December 9, 1992. Range, 500,000 kilometers (310,000 miles). P-41474

This color image of North-East Africa and Arabia was taken as Galileo left the Earth en route to Jupiter.

13. North Polar Region of Moon

View of the north pole region of the Moon with north pole to the lower left (not visible in this picture) of this mosaic of images. The view in the upper left is toward the horizon across the volcanic lava plains of Mare Imbrium. The prominent crater with the central peak is Pythagoras, an impact crater some 130 kilometers (80 miles) in diameter. December 7 and 8, 1992. Range, 121,000 kilometers (75,000 miles). P-41432



This image was taken through the violet filter of Galileo's imaging system during Galileo's second, and final, flyby of the Earth-Moon system. According to team scientists, the viewing geometry that resulted as the spacecraft passed over the lunar north pole and the low sun-angle illumination provided a unique opportunity to assess the geologic relationships among the smooth plains, cratered terrain and impact ejecta deposits in this region of the Moon.

Galileo's images of the Moon are similar in resolution to the pictures the Voyager spacecraft took of Jupiter's moons. However, when Galileo reaches Jupiter, it will be ten, even several hundred times closer to Jupiter's moons than Voyager was. This means that Galileo's images of the Jovian moons will have a resolution hundreds of times better than that seen in these pictures of our Moon.

14. Earth-Moon Conjunction

This remarkable view of the Moon in orbit about Earth was taken 8 days after the Earth/Moon 2 Encounter. The Moon is in the foreground; its orbital path is from left to right. At the bottom of Earth's disk, Antarctica is visible through clouds. Some of the Moon's far side can also be seen. The shadowy indentation in the Moon's dawn terminator—the boundary between its dark and lit sides—is the South Pole-Aiken Basin, the largest and oldest impact basin in the solar system. December 16, 1992. Range, 6.2 million kilometers (3.9 million miles). P-41508

This image of Galileo's final view of the Earth and Moon was constructed from images taken through the violet, red, and 1.0-micron (40 millionths of an inch) infrared filters. The brightly-colored Earth contrasts strongly with the Moon, which reflects only about one-fifth as much sunlight as Earth. Contrast and color have been computer-enhanced for both objects to improve visibility.

15. Ida Rotation Sequence

This montage of 14 images (the time order is right to left, bottom to top) shows Ida as it appeared in the field of view of Galileo's camera on August 28, 1993. Asteroid Ida rotates once every 4 hours, 39 minutes and clockwise when viewed from above the north pole; these images cover about one Ida "day." This sequence has been used to create a 3-D model that shows Ida to be almost croissant shaped. The earliest view (lower right) was taken from a range of 240,000 kilometers (150,000 miles), 5.4 hours before closest approach. P-44520

The asteroid Ida draws its name from mythology, in which the Greek god Zeus (equivalent to the Roman god Jupiter) was raised by the nymph Ida.

16. Asteroid Ida

Asteroid 243 Ida appears in this mosaic of 5 images to be about 56 kilometers (35 miles) in length, irregularly-shaped with numerous craters on its surface. It is a member of the Koronis family of asteroids. August 28, 1993. Ranges, 3,057 to 3,821 kilometers (1,900 to 2,375 miles). The smallest objects visible in the image are 70 meters (230 feet) across. P.42964

This view of Ida was taken about 3-1/2 minutes before the spacecraft made its closest approach to the asteroid, when Galileo flew within 2,400 kilometers (1,500 miles) from Ida at a relative velocity of 12.4 km/sec (28,000 mph) at 9:52:05 PDT. Asteroid and spacecraft were 441 million kilometers (274 million miles) from the Sun. The camera's clear filter was used to produce this extremely sharp picture.

Ida is the second asteroid ever encountered by a spacecraft. It is more than twice as large as Gaspra, the first asteroid observed by Galileo in October 1991. Ida is an irregularly shaped asteroid placed by scientists in the S class (believed to be like stony or stony- iron meteorites). It is a member of the Koronis family, presumed fragments left from the breakup of a larger asteroid in a catastrophic collision. As the Koronis family is still closely grouped, scientists initially assumed that Ida was a relatively young asteroid, with a "youthful" surface.

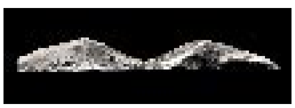
This view shows numerous craters, including many degraded craters larger than any seen on Gaspra. The extensive cratering seems to dispel theories about Ida's surface being geologically youthful (in which case there would have been relatively few craters). This view also seems to rule out the idea that Ida is a double body. The south pole is in the dark side of this image near the middle of the asteroid.

Why Pick Gaspra? Why Pick Ida?

NASA policy requires that all missions which pass through the asteroid belt between Mars and Jupiter consider a close observation of an asteroid if at all possible. So, Galileo's Mission Designers checked out more than 4,000 asteroid orbits, looking for flyby candidates that would be compatible with Galileo's VEEGA (Venus-Earth-Earth-Gravity Assist) trajectory. The leading contenders were then more closely examined with trajectory optimization software to determine which would be the best target, much like the process of planning interesting detours on a long driving trip while staying within budget and not exceeding total vacation time. In the end, Gaspra and Ida were chosen based on their accessibility, expecially their low propellant cost (from the short detour that Galileo would be required to take to see them). This double asteroid option resulted in the scientific benefit of Galileo visiting two very different S-type asteroids.

17. Ida's Limb

This high resolution view of the limb of Ida shows many small craters and some grooves on the surface, which give clues to understanding the history of this heavily impacted object. Prominent in this view is a 2-kilometer-deep (1.2 mile deep) "valley" seen in profile on the limb. August 28, 1993. Range, 2,480 kilometers (1,540 miles). P-44130



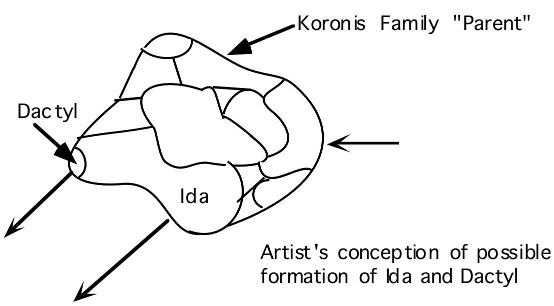
The Galileo imaging system captured this picture of the limb of the asteroid 243 Ida about 46 seconds after its closest approach on August 28, 1993. It is the highest-resolution image of an asteroid's surface ever captured, and shows details as small as about 50 meters (164 feet).

This image is one frame of a mosaic of 15 frames shuttered near Galileo's closest approach to Ida. Since the exact location of Ida in space was not well-known before the Galileo flyby, the mosaic was estimated to have only about a 50 percent chance of capturing Ida. Fortunately, this single frame did successfully image a part of the sunlit side of Ida.

The area seen in this frame shows some of the same territory seen in a slightly lower resolution full-disc mosaic of Ida, but from a different perspective. This limb profile and the stereoscopic effect between this image and the full-disc mosaic will permit detailed refinement of Ida's shape in this region.

18. Ida and Dactyl

This color-enhanced picture shows both asteroid 243 Ida and Dactyl. Ida (left) is about 56 kilometers (35 miles) long and Dactyl (right) is about 1.5 kilometers (1 mile) across in this view. Although appearing to be "next" to Ida, Dactyl is actually in the foreground, about 80 kilometers (48 miles) closer to the spacecraft than Ida is. The brighter areas, appearing bluish in the picture, suggest a difference in the abundance or composition of iron-bearing minerals in those areas. Dactyl is not identical in spectral properties to any area of Ida in view here, though its overall similarity in reflectance and general spectral type suggests that it is made of basically the same rock types. About 14 minutes before closest approach on August 28, 1993. Range, 10,500 kilometers (6,500 miles). P-44131



Artist's conception of possible formation of Ida and Dactyl

This color picture is made from a sequence of images in which Ida's moon was originally discovered.

This picture is made from images through the 4100-angstrom (violet; 16 millionths of an inch), 7560 A (infrared; 30 millionths of an inch) and 9680 A (infrared; 38 millionths of an inch) filters. The color is enhanced in the sense that the camera is sensitive to near-infrared wavelengths of light beyond human vision; a natural color picture of this asteroid would appear mostly gray. Shadings in the image indicate changes in illumination angle on the many steep slopes of this irregular body as well as subtle color variations due to differences in the physical state and composition of the soil.

Combining this data with further imaging data and more detailed spectra from Galileo's near- infrared mapping spectrometer, may allow scientists to determine whether the larger parent body--of which Ida, its moon and some other asteroids are assumed to be fragments--was a heated, differentiated object or was made of relatively unaltered primitive chondritic (i.e. having small, rounded grains about 1 to 5 mm (0.04 to 0.2 inches) in their interiors) material.

Shortly after the discovery, Galileo scientists found it unlikely that the moon is a passing body caught in Ida's gravity. They also doubt that the moon is a piece of Ida knocked loose by a smaller projectile, especially since Ida and Dactyl's bulk compositions differ slightly. Instead, scientists are theorizing that the two are siblings of a "family" of asteroids formed hundreds of millions of years ago when a larger, 100-kilometer-wide asteroid was shattered in a great collision. Instead of fragments shooting straight out from the impact, the exploding asteroid may have produced jets of material carrying two or more objects out together. Those objects could then be captured, gravitationally, around each other.

Thus, a family of asteroids could have been created as a result of such an impact. Ida belongs to the Koronis family that travels in the main Asteroid Belt between Mars and Jupiter. Gaspra, the asteroid visited by Galileo in October 1991, is a member of the Flora family.

The Dynamics of an Asteroid
(excerpted from *"Solving for Dactyl's Orbit and Ida's Density"*
in *The Galileo Messenger #35; December, 1994)*

[*Although Ida and Dactyl were photographed near each other, scientists needed to use detective work and some circumstantial evidence to prove that Dactyl was a satellite.This article shows that finding Dactyl's orbit and period was far from straightforward, and that the result also tells us something about Ida's mass and composition!*]

Galileo's discovery that Ida has a satellite (now known as Dactyl) suggests that satellites orbiting asteroids may be a commonplace occurrence. Dactyl and Ida appear in 47 Galileo images. Their locations in these images were used to estimate Dactyl's orbit and Ida's bulk density, which is of great interest because it may indicate whether Ida is composed of rocks that have been thermally processed deep within a collisionally destroyed planetesimal. Density calculations were based on an Ida volume of 16,100 cubic kilometers, which was determined from an accurate model of the shape of Ida based on Galileo's images. While Dactyl's orbit is of interest, its greatest significance is in providing the first accurate estimate of an S (stony)-type asteroid's density--another achievement by Galileo!

It became clear almost immediately that the mass (or, for a given volume, density) of Ida could not be solved at the same time as Dactyl's orbit. Instead, a series of Dactyl orbits were generated for a range of Ida mass/density values--from 1.5 to 4.0 grams per cubic centimeter. For each density value, there is a unique orbit; over this range of densities, these orbits differ greatly. For Ida densities less than about 2.1 grams per cubic centimeter, the orbits are just barely hyperbolic. For higher Ida densities, the orbits are elliptical with a large apoapsis (farthest point from Ida), a periapsis (nearest point to Ida) of around 80-85 km, and periods that range from just over a day to many tens of days. At a density of about 2.8 grams per cubic centimeter,, the orbit is nearly circular (about 82 by 98 km) with a period of about 27 hours. For even higher densities, the elliptical orbits have apoapses of about 95-100 km, with periapses that decrease with increasing density. For an Ida density greater than about 2.9 grams per cubic centimeter, the periapsis is less than about 75 km and the period is less than 24 hours.

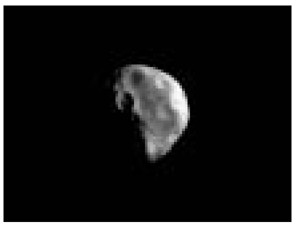
Dynamical studies show that orbits with periapses less than about 75 km from Ida are unstable and either collide with, or escape from, Ida--thus, orbit solutions are not physically possible that correspond to an Ida density of about 2.9 grams per cubic centimeter or greater.

At the other extreme, hyperbolic and even highly elliptical orbits around Ida are very unlikely. The observed speed of Dactyl around Ida for any of the orbit solutions is no more than about 10 m/s, about the speed of a fast run or a slowly thrown baseball. Calculations indicate that the chance of a random
piece of asteroidal material the size of Dactyl passing by Ida at that speed, just when Galileo was observing it, is about 2×10^{-17}. In addition, if Dactyl were in a hyperbolic or highly elliptical orbit, it should have been seen by the Hubble Space Telescope (HST) when it observed the region around Ida over an 8-hour period on April 26, 1994 . HST would have easily seen Dactyl had it been more than about 700 km from Ida. Combining these two restrictions gives a preliminary estimate for Ida's density of 2.2 to 2.9 grams per cubic centimeter, and shows that Dactyl is, in fact, a satellite of Ida's. Allowing for a +/- 12-percent uncertainty in the modeled volume of Ida increases the range to 2.0 to 3.2 grams per cubic centimeter.

This density range is surprisingly limited and suggests that Ida is fairly porous and/or made of fairly light rocks. This result excludes several classes of dense igneous rocks that had previously been suggested as the primary components of Ida's composition. Clearly, Ida is neither all ice nor all iron.

19. Highest-Resolution Image of Dactyl

This image is the most detailed picture of Dactyl, the newly discovered moon of asteroid Ida. Dactyl is surprisingly round, measuring about 1.2 x 1.4 x 1.6 kilometers (0.75 x 0.87 x 1 mile). More than a dozen craters larger than 80 meters (250 feet) in diameter are clearly evident. The larger crater on the terminator is about 300 meters (1,000 feet) across. August 28, 1993. Range, 3,900 kilometers (2,400 miles). P-44297



Shuttered through the camera's broadband clear filter as part of a 30-frame mosaic designed to image the asteroid itself, this frame fortuitously captured the previously unknown moon just over 4 minutes before the spacecraft's closest approach to Ida. Features as small as about 78 meters (250 feet) are visible on the surface of the moon. At the time this image was shuttered, Ida was about 90 kilometers (56 miles) away from the moon, outside this frame to the left and slightly below center.

The large number of craters indicates that the moon has suffered numerous collisions from smaller solar system debris during its history. Craters are seen on *all* solid bodies in the solar system in which weathering doesn't occur (micrometeoroid bombardment is a form of weathering--that's why the features are softened and a regolith (an outer layer of fine soil and loose rocks) exists), and even a few there as well.

How do you name an asteroid?

Just like a newborn baby, Ida's tiny moon needed a name. But, unlike a human infant, the moon's name would have to be approved by the International Astronomical Union (IAU). As discoverers of the moon, the Galileo Project had the honor of recommending a name to the IAU, which approved the name Dactyl in the fall of 1994.

Members of the Galileo flight team came up with some suggestions of their own, including the lighthearted "Ho" (thus favoring one state over 49 others) and "Lupino" (the late Ida Lupino being a well-known actress in the 1930's and 40's). The Galileo Project invited the general public to suggest names, and it was one of those suggestions that gave Dactyl its name.

The name is derived from the Dactyli, a group of Greek mythological beings who lived on Mount Ida,where the infant Zeus was hidden from his father Crenus, who knew that Zeus could one day depose him. In some accounts, Zeus—whose Roman name is Jupiter—was raised by the nymph Ida and protected by the Dactyli, who danced around the cave in which Zeus was hidden to make noise which would drown out the infant Zeus's crying. Modern parents, of course, prefer to use the stereo.

Cratering and the Earth

Cratering affects the Earth's environment, too. The Earth's atmosphere protects us from the multitude of small debris, the size of grains of sand or pebbles, thousands of which pelt our planet every day, and from most stony meteoroidsup to about 10 meters in diameter. But larger falls can have a serious impact: for example, the 1908 Tunguska event (which leveled 2,200 square kilometers of Siberian forest) was a stony meteorite in the 100-meter class. The famous meteor crater in northern Arizona, some 1219 meters (4,000 feet) in diameter and 183 meters (600 feet) deep, was created 50,000 years ago by a nickel-iron meteorite perhaps 60 meters in diameter. Falls of this class occur once or twice every 1000 years.

There are now over 100 ring-like structures on Earth recognized as definite impact craters. Most of them are not obviously craters, their identity masked by heavy erosion over the centuries, but the minerals and shocked rocks present make it clear that impact was their cause.

What have we learned about asteroids from Galileo's flybys?

Although scientists are still working with data from Galileo's asteroid flyby data, we have discovered a great deal so far about asteroids.

The main thing noticable about Gaspra's surface are major depressions, indentations, ridges, and craters. Some of these craters are as wide as 1.5 kilometers--indicating, for example, an impact with a body 100 meters (330 feet) in size, traveling 5 kilometers per second (3.1 miles per second). Gaspra has probably existed in its present form for the last 200 to 500 million years. Another initial observation is that the albedo (or reflectivity) is relatively homogeneous, although there are noticeable variations in albedo and color at about the 10 percent level. Some data suggest compositional differences between Gaspra's northern and southern hemispheres.

Since the gravitational force is so low, when something impacts with Gaspra, most of the dust and material from the resulting collision fly off the asteroid. With these conditions, scientists expected to see sharply defined craters and ridges, since there should have been little, if any, surface rubble (called regolith). What is surprising about Gaspra, then, is its subdued appearance. There is a small layer of regolith on the surface. As yet, scientists cannot tell how deep this layer may be, but initial estimates are from a few centimeters to a few meters. Scientists did note, with relief, that the Dust Detector registered no increase in dust impacts during the encounter, indicating a relatively "clean" environment around the asteroid.

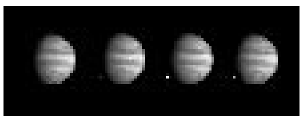
Other data from the Gaspra flyby suggested that the asteroid may have a magnetic field. If Gaspra has a permanent magnetic moment, the finding would have bearing on its thermal history, have implications for the history of the magnetic field of the early solar system, and give us more reason to believe some asteroids are very rich in iron or iron-nickel alloys of considerable economic value.

Analysis of Dactyl's possible orbit provided the first accurate estimate of an S-type (stony iron type) asteroid's density--another achievement by Galileo! Preliminary estimates of Ida's density are in the range of 1.9 to 3.2 grams per cubic centimeter. This density range is surprisingly well constrained and suggests that Ida is fairly porous and/or made of fairly light rocks. This result already excludes several classes of dense igneous rocks that had previously been suggested as the primary components of Ida's composition.

Further work on the stability of Dactyl's possible orbits, as well as a more precise analysis of Dactyl, may lead to a better determination of both the density of Ida and the orbit of Dactyl. These, combined with other ongoing work involving the color, spectral properties, and geology of Ida's surface are expected to lead to major advances in our knowledge of the nature of asteroids and what they can tell us about the birth of the planets.

20. Shoemaker-Levy 9: The Last Impact—W

These four images of Jupiter and the impact of fragment W of Comet Shoemaker-Levy 9 were taken at intervals of 2 1/3 seconds. The first image shows no impact. In the next three images, a point of light appears (left of Jupiter's terminator), brightens so much as to saturate its picture element, and then fades, seven seconds after the first picture. July 22, 1994. Range, 238 million kilometers (148 million miles). P-44542



While most of the observations of Comet Shoemaker-Levy 9's collision with Jupiter were made from Earth or Earth-orbiting observatories, Galileo had the best seat in the house. Only Galileo was able to directly see the crash sites; from the Earth, the collision site was on Jupiter's back side, out of view of Earth.

The location is approximately 44 degrees; dark spots to the right are from previous impacts. Jupiter is approximately 60 picture elements in diameter. The images were taken using the green filter (visible light).

Galileo tape-recorded most of its observations of the Shoemaker- Levy impact and played the tape back selectively.

Scientists now believe that the point of light in this picture and other Galileo data shows the effects of the meteor bolides (the comet fragment entering Jupiter's atmosphere) and is not related to the subsequent explosion and fireball. Once all the Galileo, Hubble Space Telescope and ground-based data are combined, an excellent start-to-finish characterization of these remarkable phenomena will be available.

What have we learned from the Shoemaker-Levy comet collision?

Because of its unique vantage point, Galileo's data from the Shoemaker-Levy/9 comet collision with Jupiter has been integral to explaining the timing of events in the collisions. Galileo's remote sensing experiments detected 8 separate impacts (specifically, fragments G, H, K, L, N, Q1, R and W).

Preliminary data analyses from three of Galileo's instruments indicated that one of the SL9 fragments exploded into a 7-km (4-mile)-diameter fireball. This Fragment G fireball on July 18 1994, when first detected by the Ultraviolet Spectrometer (UVS) and Photopolarimeter-Radiometer (PPR), was about 7,600 kelvins (13,000 degrees Fahrenheit), which is hotter than the Sun's surface. Five seconds later, the Near-Infrared Mapping Spectrometer (NIMS) detected it, recording the fireball's expansion, rise, and cooling for a minute and a half, until it was hundreds of kilometers across and only about 400 K (260 deg F). Galileo has thus provided a unique data set on SL9, that is, the only profile of the size and temperature of the fireball during the first few minutes following the impact itself.

Based on NIMS data, we know that the super hot fireballs associated with fragments G and R lasted about 1 minute (before cooling sufficiently to be invisible to NIMS). We also know (from NIMS) that the plume ejecta began falling back into the atmosphere about 6 minutes later, getting brighter and brighter for the 3 minutes observed. Ground-based data indicate that the total splash phase for each of the two fragments lasted about 10 minutes, with peak brightness reached at about 5 minutes after initial detection. The ejecta exploded out of the atmosphere at a minimum vertical velocity of 4.3 km/s (~9,300 mph), with particles reaching at least 380 km (228 miles) high!

Galileo may help answer many questions about the collision. For example, what was the size of the comet fragments? Were they large, several kilometers in diameter, as some predicted? Or were they much smaller--only half a kilometer across--or even just loosely held-together piles of rubble or wisps of dust?

A related question is how deeply the comet pieces penetrated into Jupiter's atmosphere before exploding. Single, large, solid fragments would have been expected to penetrate further and bring up water from Jupiter's presumed water-rich atmospheric layers, while rubble piles or rubble swarms might only have caused meteor storms in the upper atmosphere with no deep penetration. Preliminary spectroscopic data imply that the fragments did not penetrate very deeply, since little or no water was splashed up into the stratosphere.

Another interesting question is why Jupiter's icy satellite Europa did not reflect the bright flashes from the dark side of Jupiter, as expected. Europa's shadowed, reflective, icy surface should have served as an excellent mirror for the brilliant flashes and subsequent glowing fireballs. But it didn't happen that way. Galileo may be best able to answer questions about optical flashes.

Perhaps the most perplexing question is what caused those immense black patches to remain in Jupiter's high atmosphere. The largest patches are bigger than the whole planet Earth and much darker and more prominent than the Great Red Spot. Initially, they were expected to fade and disappear in a few days, but they persisted for months afterwards--even a year in some wavelengths. Conceivably, as Galileo nears its target, it will also be able to help explain these aspects of the SL9 impacts at Jupiter.