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TITLE: **VIEWS OF THE SOLAR SYSTEM**

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Solar System Home

Views Of The Solar System

Compiled by Calvin J. Hamilton, Los Alamos National Laboratory.

Views of the Solar System has been created as an educational tour of the solar system. It contains images and information about the Sun, planets, moons, asteroids and comets found within the solar system. The image processing for many of the images was done by the author.

This tour uses hypertext to allow space travel by simply clicking on a desired planet. This causes information and images about the planet to appear on screen. While on a planet page, hyperlinks travel to pages about the moons and other relevant available resources. Unusual terms are linked to and defined in the *Glossary* page. Statistical information of the planets and satellites can be browsed through lists sorted by name, radius and distance. *History of Space Exploration* contains information about rocket history, early astronauts, space missions, spacecraft and detailed chronology tables of space exploration. The *Table of Contents* page has links to all of the various pages within *Views Of The Solar System.*

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- **The Solar System**


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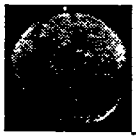
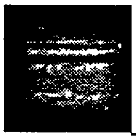
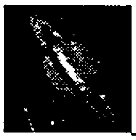
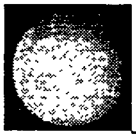
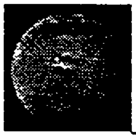
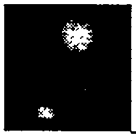
 Mars

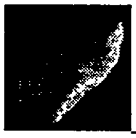
 Jupiter

 Saturn

 Uranus

 Neptune

 Pluto

 Asteroids

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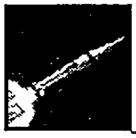
-  History of Space Exploration
- **Sorted Lists of Planets and Satellites**

- Sorted by Name
- Sorted by Radius
- Sorted by Distance

- **Glossary**
- **Acknowledgements**

From time to time, new information and new images will be added to this tour. If you have any additional information, images, corrections or ideas which would enhance this tour please contact:

Calvin J. Hamilton (cjhamil@lanl.gov)

- **Other Compiled Tours**
    - by Ken Edgett, Arizona State University.
    - Jet Propulsion Laboratory, Pasadena, California.
    - Regional Planetary Image Facility, Smithsonian Institution, Washington DC.
    - Royal Greenwich Observatory, UK.
    - National Solar Observatory Exhibit.
    - Historical Space Archive
- Index of Images Used in the Solar System Tour
- Educator's Comet Guide.
- Jet Propulsion Laboratory SPACE CALENDAR.

Space Related Links

Space Agencies

- NASA Home Page

- NASA/Kennedy Space Center
- NASA/JSC Image Science Division
- JPL Home Page
- European Space Agency
- Space Telescope Science Institute (STScI)

Hot Topics

- Local Images of the Comet Impact on Jupiter
- Shoemaker–Levy 9/Jupiter Collision Information & Images
- Shoemaker–Levy 9/Jupiter Images from STSCI
- NASA "Hot Topics"
- Comet Shoemaker–Levy 9 Home Page From SEDS
- Comet Shoemaker–Levy 9 Photo
- Comet Shoemaker–Levy 9 Impact from JPL
- Black Hole in Galaxy M87
- Radar Images of the Earth
- International Space Station
- Political Space Information

Other Space Related Items

- University of Oregon
- Frequently Asked Questions (Sci.Space)
- Total Solar Eclipse '94 Home Page
- sci.space.news
- US/Russian Space Server
- Shuttle Mission Information
- Planetary Image Finders
- Venus Magellan Image Browser
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Net Resources

- List of net resources at STSCI
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Last Update

August 26, 1994

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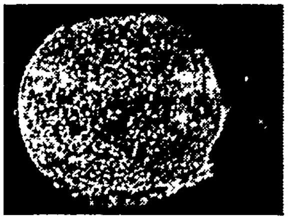


Sun

Net Resources For The Sun:

- National Solar Observatory Exhibit.
- Current Solar Images.

Chronology of Sun Exploration

The sun is the most prominent feature in our solar system. It is the largest object and contains approximately 98% of the total solar system mass. One hundred and nine Earths would be required to fit across the Sun's disk, and its interior could hold over 1.3 million Earths. The Sun's outer visible layer is called the photosphere and has a temperature of 6,000°C (11,000°F). This layer has a mottled appearance due to the turbulent eruptions of energy at the surface.

Solar energy is created deep within the core of the sun. It is here that the temperature (15,000,000° C; 27,000,000° F) and pressure (340 billion times Earth's air pressure at sea level) is so intense that nuclear reactions take place. This reaction causes four protons or hydrogen nuclei to fuse together to form one alpha particle or helium nucleus. The alpha particle is about .7 percent less massive than the four protons. The difference in mass is expelled as energy and is carried to the surface of the sun where it is released as light and heat. Every second 700 million tons of hydrogen are converted into helium *ashes*. In the process 5 million tons of pure energy is released; therefore, as time goes on the Sun is becoming lighter.

The chromosphere is above the photosphere. Solar energy passes through this region on its way out from the center of the sun. Faculae and flares arise in the chromosphere. Faculae are bright luminous hydrogen clouds which form above regions where sunspots are about to form. Flares are bright filaments of hot gas emerging from sunspot regions. Sunspots are dark depressions on the photosphere with a typical temperature of 4,000°C (7,000°F).

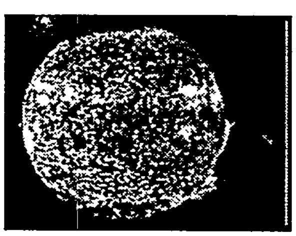
The corona is the outer part of the sun's atmosphere. It is in this region that *prominences* appears. Prominences are immense clouds of glowing gas that erupt from the upper chromosphere. The outer region of the corona stretches far into space and consists of particles traveling slowly away from the sun. The corona can only be seen during total solar eclipses. (See Solar Eclipse Image).

The Sun appears to have been active for 4.6 billion years and has enough fuel to go on for another five billion years or so. At the end of its life, the Sun will start to fuse helium into heavier elements and begin to swell up, ultimately growing so large that it will swallow the Earth. After a billion years as a red giant, it will suddenly collapse into a white dwarf -- the final end product of a star like ours. It may take a trillion years to cool off completely.

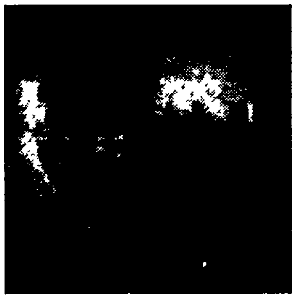
Sun Statistics

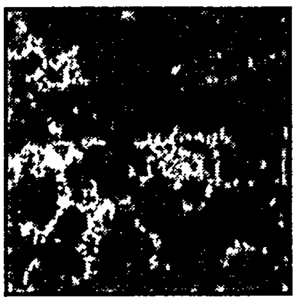
- Mass: 1.989 x 10^30 kg
- Radius: 695,000 km
- Surface Temperature: 5,770° K
- Luminosity: 3.827 x 10^33 ergs/sec
- Age: 4.5 billion years
- Principal Chemistry:
  - Hydrogen: 92.1%
  - Helium: 7.8%
  - Oxygen: 0.061%
  - Carbon: 0.30%
  - Nitrogen: 0.0084%
  - Neon: 0.0076%
  - Iron: 0.0037%
  - Silicon: 0.0031%
  - Magnesium: 0.0024%
  - Sulfur: 0.0015%
  - All others: 0.0015%

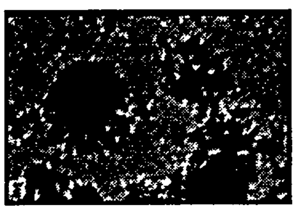
Views of the Sun

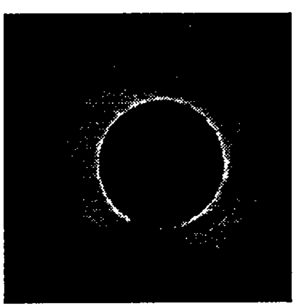


Sun Prominence: This image was acquired from NASA's Skylab space station on December 19, 1973. It shows one of the most spectacular solar flares ever recorded, propelled by magnetic forces, lifting off from the Sun. It spans more than 588,000 km (365,000 miles) of the solar surface. In this photograph the solar poles are distinguished by a relative absence of supergranulation network, and a much darker tone than the central portions of the disk.


X–Ray Image: This is an X–ray image of the sun obtained February 21, 1994. The brighter regions are sources of increased X–ray emissions.


Solar Magnetic Fields: This image was acquired February 26, 1993. The dark regions are locations of positive magnetic polarity and the light regions are negative magnetic polarity.


Sun Spots: This image shows the region around a sunspot. Notice the mottled appearance. This granulation is the result of turbulent eruptions of energy at the surface.


Solar Eclipse: This is a view of a solar eclipse.

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Voyage to Mercury

Mercury

Chronology of Mercury Exploration

Mercury was named by the Romans after the messenger of the gods because it seemed to move more quickly than any other planet. Mercury is the inner most planet in our solar system and is the second smallest one. Pluto is the smallest. Both Saturn and Jupiter have moons that are larger than Mercury such as Titan and Ganymede. Jupiter's moons Io, Europa, and Callisto are very close in size to Mercury.

Mercury resembles our moon with lunar–like terrain but differs with respect to its density. Mercury has a density of 5.43 gm/cm^3 which is similar to the density of the Earth. This density indicates that its core has an iron composition like the Earth. The core probably takes up about 70% to 80% of the planet's radius with the outer region largely composed of silicate rocks.

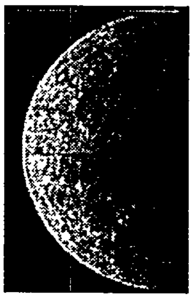
Mercury has almost no atmosphere. The atmosphere on Earth helps keep a uniform temperature from day to night. On Mercury, due to its closeness to the Sun, the temperature rises to over 400° C (750° F) during the day. At night, because of the lack of atmosphere to help retain heat, the temperature drops to −180° C (–300°F).

Mercury Statistics

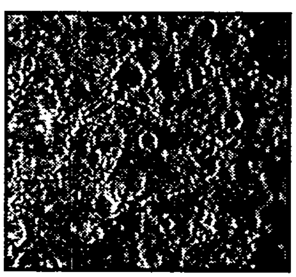
- Mean distance from the Sun: 0.3871 AU (5.791 x 10^7 km)
- Equatorial radius: 2,439 km
- Mass: 3.303 x 10^23 kg
- Mean density: 5.43 gm/cm^3
- Rotational Period: 58.65 days
- Orbital period: 87.969 days
- Mean orbital velocity: 47.89 km/s
- Equatorial surface gravity: 2.78 m/s^2
- Equatorial escape velocity: 4.3 km/s

- Orbital eccentricity: 0.2056
- Obliquity: 0°
- Orbit Inclination: 7.004°
- Visual Geometric Albedo: 0.12
- Mean surface temperature: 452°K
- Maximum surface temperature: 700°K
- Minimum surface temperature: 100°K

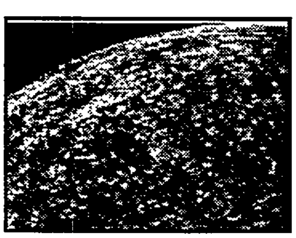
Views of Mercury



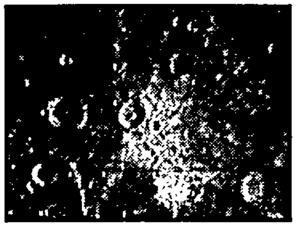
Mercury: This photomosaic of Mercury was constructed from photos taken by Mariner 10 six hours after the spacecraft flew past the planet on March 29, 1974. The north pole is at the top and the equator extends from left to right about two–thirds down from the top. A large circular basin, about 1,300 kilometers (800 miles) in diameter, is emerging from the day– night terminator at left center. Bright rayed craters are prominent in this view of Mercury. One such ray seems to join in both east–west and north–south directions. *(Courtesy NASA/JPL)*



Hills of Mercury: "Weird terrain" best describes this hilly, lineated region of Mercury. This area is at the antipodal point (directly on the opposite side of the planet) from the large Caloris basin. The shock wave produced by the Caloris impact was reflected and focused to this antipodal point, thus jumbling the crust and breaking it into a series of complex blocks. The area covered is about 100 km (62 mi) on a side. *(Courtesy NASA/JPL)*



Southwest Mercury: The southwest quadrant of Mercury is seen in this image taken March 29, 1974, by the Mariner 10 spacecraft. The picture was taken four hours before the time of closest approach when Mariner was 198,000 km (122,760 mi) from the planet. The largest craters seen in this picture are about 100 km (62 mi) in diameter. *(Courtesy NASA/JPL)*



Mercury Close Up: Mercury's surface is similar to that of Earth's Moon, where a history of heavy cratering is followed by volcanic filling. The small, bright halo crater in the center is 10 km (6 mi) in diameter, while the prominent crater farther left has a central peak 30 km (19 mi) across. The darker, lightly cratered area (upper left) may be an ancient lava flow. *(Courtesy NASA/JPL)*

Solar System Home
Voyage to Venus

Venus

Net Resources For Venus:

- Magellan Image Browser

Chronology of Venus Exploration

Venus has often been called Earth's sister planet. They are similar in size and mass; however, conditions on Venus are not at all like the earth. Venus is surrounded by a heavy atmosphere (95 times as dense as Earth's) which is composed mainly of carbon dioxide (CO_2). There is very little water on the planet. The clouds that can be seen are not made up of water but of sulfuric acid. The surface temperature on Venus is about 482° C (900° F). This high temperature is primarily due to the greenhouse effect caused by the heavy atmosphere of carbon dioxide. Sunlight passes through the atmosphere to heat the surface of the planet. The heat is then radiated but is trapped by the dense atmosphere. It is not allowed to escape into space. This makes Venus hotter than Mercury.

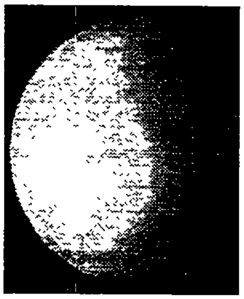
Venus is the second planet from the Sun. It takes 225 days to orbit the sun and 243 days to rotate one time – quite unlike the Earth's 24 hour rotation. Venus rotates from east to west. This means that for an observer on Venus, the sun would rise in the west and set in the east.

Venus Statistics

- Mean distance from the Sun: 0.7233 AU (1.082 x 10^8 km)
- Equatorial radius: 6,051 km
- Mass: 4.87 x 10^24 kg
- Mean density: 5.25 gm/cm^3
- Rotational Period: 243.01 days
- Orbital period: 224.7 days
- Mean orbital velocity: 35.03 km/s

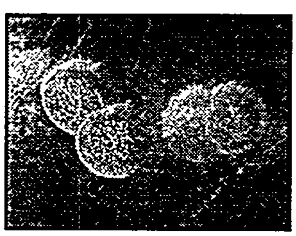
- Equatorial surface gravity: 8.6 m/s^2
- Equatorial escape velocity: 10.4 km/s
- Orbital eccentricity: 0.0068
- Obliquity: 178°
- Orbit Inclination: 3.39°
- Visual Geometric Albedo: 0.59

Views of Venus

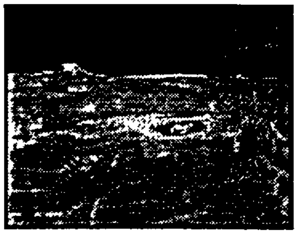


Galileo Image of Venus: This image of Venus was acquired by the Galileo spacecraft. It shows the thick cloud coverage that prevents optical observation of the surface of Venus. Only through radar mapping is the surface reveiled.

Venus: This is a global view of the surface of Venus centered at 180 degrees east longitude. Simulated color is used to enhance small–scale structure.

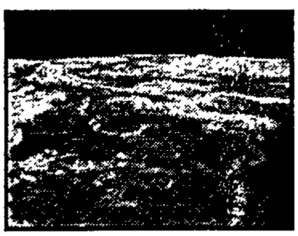


Pancakes. This image of the eastern edge of Alpha Regio, 30 degrees south latitude, 11.8 east longitude, was acquired on November 7, 1990. It shows several circular domical hills averaging 25 kilometers (15 miles) in diameter with maximum heights of 750 meters (2475 feet). These features can be interpreted as viscous or thick eruptions of lava coming from a vent on the relatively level ground allowing the lava to flow in an even lateral pattern. *(Courtesy NASA/JPL)*



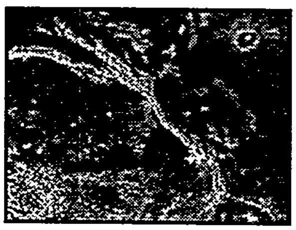
Gula Mons and Crater Cunitz. A portion of Western Eistla Regio is displayed in this three dimensional perspective view of the surface of Venus. The viewpoint is located 1,310 kilometers (812 miles) southwest of Gula Mons at an elevation of 0.78 kilometers (0.48 mile). The view is to the northeast with Gula Mons appearing on the horizon. Gula Mons, a 3 kilometer (1.86 mile) high volcano, is located at approximately 22 degrees north latitude, 359 degrees east longitude. The impact crater Cunitz, named for the astronomer and mathematician Maria Cunitz, is visible in the center of the image. The crater is 48.5 kilometers (30 miles) in diameter and is 215 kilometers (133 miles) from the viewer's position. *(Courtesy NASA/JPL)*

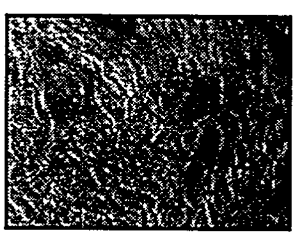
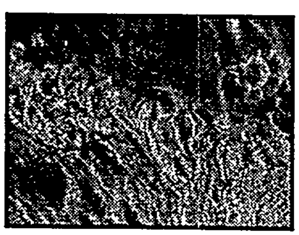
Eistla Regio – Rift Valley. A portion of Western Eistla Regio is displayed in this three dimensional perspective view of the surface of Venus. The viewpoint is located 725 kilometers (450 miles) southeast of Gula Mons. A rift valley, shown in the foreground, extends to the base of Gula Mons, a 3 kilometer (1.86 miles) high volcano. This view is facing the northwest with Gula Mons appearing at the right on the horizon. Sif Mons, a volcano with a diameter of 300 kilometers (180 miles) and a height of 2 kilometers (1.2 miles), appears to the left of Gula Mons in the background. *(Courtesy NASA/JPL)*



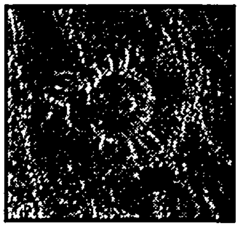
Eistla Regio. A portion of Western Eistla Regio is displayed in this three dimensional perspective view of the surface of Venus. The viewpoint is located 1,100 kilometers (682 miles) northeast of Gula Mons at an elevation of 7.5 kilometers (4.6 miles). Lava flows extend for hundreds of kilometers across the fractured plains shown in the foreground, to the base of Gula Mons. This view faces the southwest with Gula Mons appearing at the left just below the horizon. Sif Mons appears to the right of Gula Mons. The distance between Sif Mons and Gula Mons is approximately 730 kilometers (453 miles). *(Courtesy NASA/JPL)*

 **Lakshmi Planum.** The southern scarp and basin province of western Ishtar Terra are portrayed in this three dimensional perspective view. Western Ishtar Terra is about the size of Australia and is a major focus of Magellan investigations. The highland terrain is centered on a 2.5 km to 4 km high (1.5 mi to 2.5 mi high) plateau called Lakshmi Planum which can be seen in the distance at the right. Here the surface of the plateau drops precipitously into the bounding lowlands, with steep slopes that exceed 5% over 50 km (30 mi). *(Courtesy NASA/JPL)*

  **Ammavaru Lava Flows.** This is a Magellan radar image mosaic of Venus, centered at 47 degrees south latitude, 25 degrees east longitude in the Lada region. The scene is approximately 550 kilometers (341 miles) east–west by 630 kilometers (391 miles) north–south. The mosaic shows a system of east–trending radar– bright and dark lava flows encountering and breaching a north– trending ridge belt (left of center). Upon breaching the ridge belt, the lavas pool in a vast, radar–bright deposit (covering approximately 100,000 square kilometers [right side of image]). The source caldera for the lava flows, named Ammavaru, lies approximately 300 kilometers (186 miles) west of the scene. *(Courtesy NASA/JPL)*

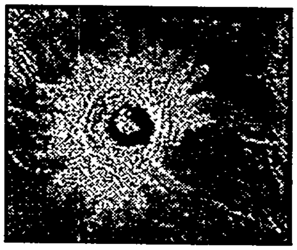
  **Alpha Regio.** These images show the Alpha Regio. The bright lineated terrain is a series of troughs, ridges, and faults that are oriented in many directions. The lengths of these features generally range from 10 kilometers (6.3 miles) to 50 kilometers (31.3 miles). The topographic elevation within Alpha Regio varies over a range of 4 kilometers (2.5 miles). Local topographic lows, whose outlines are generally controlled by structures within the central region, are relatively radar–dark and filled with

volcanic lavas. Source vents for this volcanism appear as bright spots within the smooth plains units. *(Courtesy NASA/JPL)*

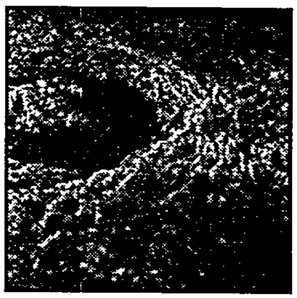


Tick. Scientists nicknamed this type of volcano a tick. About 65.6 km (40.7 mi) across at the base, this volcano has a flat, concave summit 34.8 km (21.6 mi) in diameter. The sides of the volcano are characterized by radiating ridges and valleys. The rim of the volcano to the west appears to have been breached by dark lava flows that emanated from a shallow summit pit (5.4 km/3.3 mi in diameter) and traveled west along a channel. A series of coalescing, collapsed pits 2–10 km (1.2–6.2 mi) in diameter is 10 km (6.2 mi) west of the summit rim. The black square represents missing data. *(Courtesy NASA/JPL)*

Arachnoids. Arachnoids are one of the more remarkable features found on Venus and are seen on radar–dark plains in these Magellan image mosaics of the Fortuna region. As the name suggests, arachnoids are circular to ovoid features with concentric rings and a complex network of fractures extending outward. The arachnoids range in size from approximately 50 kilometers (29.9 miles) to 230 kilometers (137.7 miles) in diameter. Since arachnoids are similar in form but generally smaller than coronae (circular volcanic structures surrounded by a set of ridges and grooves as well as radial lines), one theory concerning their origin is that they are a precursor to coronae formation. The radar–bright lines extending for many kilometers may have been caused by an upwelling of magma from the interior of the planet which pushed up the surface to form "cracks." Radar–bright lava flows are present in the 1st and 3rd image, also indicative of volcanic activity in this area. Some of the fractures cut across these flows, indicating that the flows occurred before the fractures appeared; such relations between different structures provide good evidence for relative age dating of events. At present, arachnoids are found only on Venus and can now be more closely studied with the high resolution (120 meter/0.07 mile) radar imagery from Magellan. *(Courtesy NASA/JPL)*



Golubkina. This is a Magellan image of Crater Golubkina. The 34 km (21 mi) diameter crater is characterized by terraced inner walls and a central peak, typical of large impact craters on the Earth, the Moon and Mars. The terraced inner walls take shape late in the formation of an impact crater, due to the collapse of the initial cavity created by the meteorite impact. The central peak forms due to the rebound of the inner crater floor. This crater is named after the Russian sculptor Anna Golubkina. *(Courtesy NASA/JPL)*



3D Golubkina. This is a computer generated, 3D perspective view of Crater Golubkina. *(Courtesy NASA/JPL)*

Parallel Lines. Two groups of parallel features that intersect almost at right angles are visible. The regularity of this terrain caused scientists to nickname it *graph paper* terrain. The fainter lineations are spaced at intervals of about 1 km (.6 mi) and extend beyond the boundaries of the image. The brighter, more dominant lineations are less regular and often appear to begin and end where they intersect the fainter lineations. It is not yet clear whether the two sets of lineations represent faults or fractures, but in areas outside the image, the bright lineations are associated with pit craters and other volcanic features. *(Courtesy NASA/JPL)*

Solar System Home
Home to Earth

 **Earth**

Hyper–link To Earth's Moon.

Net Resources For Earth

- Space radar images of Earth

From the perspective we get on Earth, our planet appears to be big and sturdy with an endless ocean of air. From space, astronauts often get the impression that the Earth is small with a thin, fragil layer of atmosphere. For a space traveler, the distinguishing Earth features are the blue waters, brown and green land masses and white clouds set against a black background.

Many dream of traveling in space and viewing the wonders of the universe. In reality all of us are space travelers. Our spaceship is the planet Earth, traveling at the speed of 108,000 kilometers (67,000 miles) an hour.

Earth is the 3rd planet from the Sun at a distance of about 150 million kilometers. It takes 365.256 days for the Earth to travel around the sun and 23.9345 hours for the Earth rotate a complete revolution. It has a diameter of 12,756 km, only a few hundred kilometers larger than that of Venus. Our atmosphere is composed of 78 percent nitrogen, 21 percent oxygen and 1 percent other constituents.

Earth is the only planet in the solar system known to harbor life. Our planet's rapid spin and molten nickel–iron core give rise to an extensive magnetic field, which, along with the atmosphere, shields us from nearly all of the harmful radiation coming from the Sun and other stars. Earth's atmosphere protects us from meteors as well, most of which burn up before they can strike the surface.

From our journeys into space, we have learned much about our home planet. The first American satellite, Explorer 1, discovered an intense radiation zone, now called the Van Allen radiation belts, surrounding Earth. Other findings from satellites show that our planet's magnetic field is distorted into a tear–drop shape by the solar wind. We also now know that our wispy upper atmosphere, once believed calm and uneventful, seethes with activity — swelling by day and contracting by night. Affected by changes in solar activity, the upper atmosphere contributes to weather and climate on Earth.

Besides affecting Earth's weather, solar activity gives rise to a dramatic visual phenomenon in our atmosphere. When charged particles from the solar wind become trapped in Earth's magnetic field, they collide with air molecules above our planet's magnetic poles. These air molecules then begin to glow and are known as the auroras or the northern and southern lights.

Earth Statistics

- Mean distance from the Sun: 1.0000 AU (1.4960 x 10^8 km)
- Equatorial radius: 6,378 km
- Mass: 5.976 x 10^24 kg
- Mean density: 5.52 gm/cm^3
- Rotational Period: 23.9345 hours
- Orbital period: 365.256 days
- Mean orbital velocity: 29.79 km/s
- Equatorial surface gravity: 9.78 m/s^2
- Equatorial escape velocity: 11.2 km/s
- Orbital eccentricity: 0.0167
- Obliquity: 23.4°
- Orbit Inclination: 0°
- Visual Geometric Albedo: 0.39

Views of The Earth

The following set of images show some of the wonders of our planet, *the Earth.*

South America:

This color image of the Earth was obtained by Galileo at about 6:10 a.m. Pacific Standard Time on Dec. 11, 1990, when the spacecraft was about 1.3 million miles from the planet during the first of two Earth flybys on its way to Jupiter. South America is near the center of the picture, and the white, sunlit continent of Antarctica is below. Picturesque weather fronts are visible in the South Atlantic, lower right. *(Courtesy NASA/JPL).*

**Africa:** This image, obtained from space, shows the African continent.

**Earth & Moon:**

Eight days after its encounter with the Earth, the Galileo spacecraft was able to look back and capture this view of the Moon in orbit about the Earth, taken from a distance of about 6.2 million kilometers (3.9 million miles), on December 16, 1990. The Moon is in the foreground, moving from left to right. The brightly colored Earth contrasts strongly with the Moon, which reflects only about one third as much sunlight as the Earth. Contrast and color have been computer enhanced for both objects to improve visibility. Antarctica is visible through the clouds (bottom). The Moon's far side is seen; the shadowy indentation in the dawn terminator is the south Pole/Aitken Basin, one of the largest and oldest lunar impact features. *(Courtesy NASA/JPL).*

**Antarctica:**

This image of Antarctica was taken by Galileo several hours after it flew close to the Earth on December 8, 1990. This is the first picture of the whole Antarctic continent taken nearly at once from space. Galileo was about 200,000 kilometers (125,000 miles) from Earth when the pictures were taken.

The icy continent is surrounded by the dark blue of three oceans: the Pacific to the right, the Indian to the top, and a piece of the Atlantic to the lower left. Nearly the entire continent was sunlit at this time of year, just two weeks before southern summer solstice. The arc of dark spots extending from near the South Pole (close to the center) toward the upper right is the Transantarctic Mountain Range. To the right of the mountains is the vast Ross Ice Shelf and the shelf's sharp border with the dark waters of the Ross Sea. The thin blue line along the Earth's limb marks our planet's atmosphere. *(Courtesy NASA/JPL).*

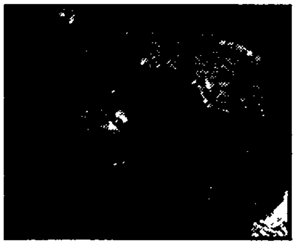
Clementine Mission:

This is a recently acquired image of the Earth from the Clementine mission.

USA:

This image is a mosaic of the United States prepared by using 16 images from the Advanced Very High Resolution Radiometer (AVHRR) sensors on the meteorological satellites NOAA–8 and NOAA–9. The images were acquired between May 24, 1984 and May 14, 1986.

On false–color infrared mosaics, vegetation appears in various tones of red instead of green. The "redness" indicates vegetation density, type and whether growing on dry land or in a swamp (a mixture of reddish vegetation and dark blue surface water produces dark tones). Grasslands appear light red, deciduous trees and croplands appear red, and coniferous forests appear dark red or maroon. Desert areas appear white and urban areas (pavement and buildings) appear bluish green. Lakes, rivers and oceans appear in various shades of blue, dark blue for deep water and light blue for shallow or turbid water. Exposed bedrock generally appears as a dark bluish–green or other dark tone. *(Courtesy USGS).*

 **Galapagos Islands:**

This image of the Galapagos Islands was taken from the space shuttle using a hand held camera. There are seven shield volcanoes in this area (Fernandina, Ecuador, Wolf, Darwin, Alcedo, Sierra Negra, and Azul) which collectively have erupted more than sixty times this century. Unlike Hawaii, these volcanoes are infrequently studied due to their inaccessibility and delicate ecology. In addition, the rugged terrain, lack of water and field support make these volcanoes difficult to map and study in the field. *(Courtesy NASA/JPL).*

 **America:**

Moon Summary

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Radius:                     1,738 km
Distance From the Earth:    384,400 km
Mass:                       7.35 x 10^22 kg
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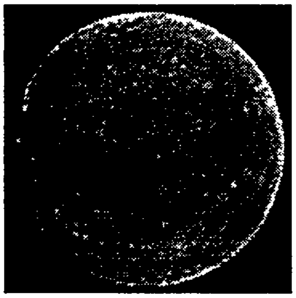
Solar System Home
Voyage to Mars



The Moon

Chronology of Moon Exploration

The Moon is about a quarter of a million miles away from the Earth. It takes 27.322 days to rotate around the Earth one time. It's rotational period is matched to that of its orbital period. This results in having the same side of the moon always facing the Earth and before the space age no one knew what the far side of the moon looked like.

Man has always wondered about the moon and whether anyone would go there. On July 20, 1969, Neil Armstrong was the first man to ever step onto the surface of the moon. He was followed by Edwin Aldrin. Both were members of the Apollo 11 flight to the moon.

Those who have set foot on the moon have found it to be very different than on the Earth. The moon has no atmosphere and air is the medium that carries sound. Without air, sound can not be heard.

On Earth the sky appears blue due to the diffraction of light in the atmosphere. Since there is no atmosphere on the moon, the sky is always black. The gravity on the moon is one sixth that of the Earth. A man weighing 180 pounds on the Earth would only weigh 30 pounds on the moon.

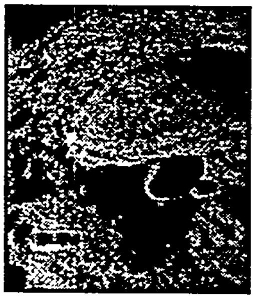
Moon Statistics

- Radius: 1,738 km
- Mass: 7.35 x 10^22 kg
- Density: 3.34 gm/cm^3
- Distance from Earth: 384,400 km
- Orbital period: 27.322 days
- Rotational period: 27.322 days
- Orbital inclination: 18.3–28.6°
- Orbital eccentricity: 0.05

- Equatorial surface gravity: 1.62 m/s^2
- Equatorial escape velocity: 2.4 km/s
- Magnitude (Vo): −12.7

Views of the Moon

The following is a collection of images showing the moon.

**Far Side of the Moon:**

This image was taken by Apollo 11 astronauts in 1969. It shows a portion of the moon's heavily cratered far side. The large crater is approximately 80 km (50 miles) in diameter. The rugged terrain seen here is typical of the farside of the Moon. *(Courtesy NASA).*

**Apollo 11:** The Apollo 11 Lunar Module ascent stage, with Astronauts Neil A. Armstrong and Edwin E. Aldrin Jr. aboard, is photographed from the Command and Service Modules (CSM) during rendezvous in lunar orbit. The Lunar Module (LM) was making its docking approach to the CSM. Astronaut Michael Collins remained with the CSM in lunar orbit while the other two crewmen explored the lunar surface. The large, dark–colored area in the background is Smyth's Sea, centered at 85 degrees east longitude and 2 degrees south latitude on the lunar surface (nearside). This view looks west. The Earth rises above the lunar horizon. *(Courtesy NASA).*

**Apollo 11 – Flag:** Astronaut Edwin E. Aldrin Jr., lunar module pilot, poses for a photograph beside the deployed United States flag during Apollo 11 extravehicular activity on the lunar surface. The Lunar Module "Eagle" is on the left. The footprints of the astronauts are clearly visible in the soil of the

moon. This picture was taken by Astronaut Neil A. Armstrong, commander, with a 70mm lunar surface camera. *(Courtesy NASA).*


Apollo 11 – Earth from the Moon: This view of the Earth rising over the Moon's horizon was taken from the Apollo 11 spacecraft. The lunar terrain pictured is in the area of Smuth's Sea on the nearside. *(Courtesy NASA).*

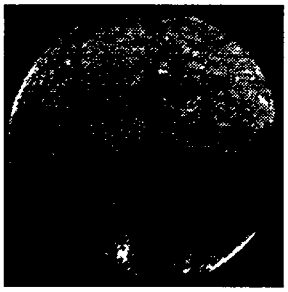

Last Apollo Mission:

This is the landing site of the last Apollo mission. It was in the valley among the Taurus–Littrow hills on the southeastern rim of Mare Serenitatis. Two of the Apollo 17 astronauts explored the valley with the aid of an electrically powered car. This image shows one of the astronauts inspecting a huge boulder that has rolled down the side of an adjacent hill.


Lunar Rover:

This is a view of the *Lunar Rover* which was used by the Apollo 17 astronauts to travel around on the moon.

Solar System Home

 **Mars**

Hyper–links to Moons of Mars:

Deimos and Phobos.

Net Resources For Mars:

- Raw Viking Images of Mars.
- **Mars Atlas.** This site provides access to detailed USGS maps of any part of Mars and to high–resolution Viking Orbiter images.

Chronology of Mars Exploration

Mars is the fourth planet from the sun and is commonly referred to as the red planet. The rocks, soil and sky have a red or pink hue. The distinct color of Mars was by stargazers throughout history. It was given its name by the Romans in honor of their god of war.

Atmosphere

The atmosphere of Mars is quite different from that of earth. It is composed mostly of carbon dioxide with small amounts of other gases. The six most common components of the atmosphere are:

- Carbon Dioxide (CO_2): 95.3%
- Nitrogen (N_2): 2.7%
- Argon (Ar): 1.6%
- Oxygen (O_2): 0.15%
- Water (H_2O): 0.03%
- Neon (Ne): 0.0003 %

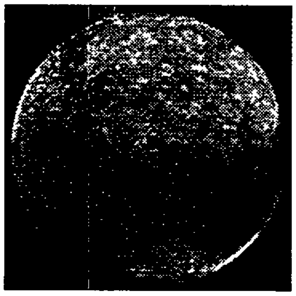
Temperature and Pressure

The average recorded temperature on Mars is –81° F (–63° C) with a maximum temperature of 20° C (68° F) and a minimum of –220° F (–140° C). The pressure on Mars is about 6.1 millibars (0.006 atm) with a maximum of 8.9 millibars and a minimum of 1 millibar. In comparison, the average pressure of the earth is 1 bar.

Mars Statistics

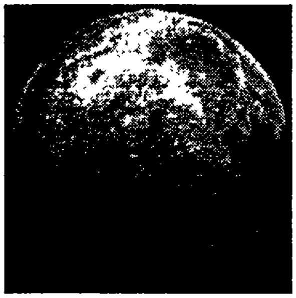
- Mean distance from the Sun: 1.5237 AU (227.94 x 10^8 km)
- Equatorial radius: 3,393 km
- Mass: 6.421 x 10^23 kg
- Mean density: 3.95 gm/cm^3
- Rotational Period: 24.6229 hours
- Orbital period: 686.98 days
- Mean orbital velocity: 24.13 km/s
- Equatorial surface gravity: 3.72 m/s^2
- Equatorial escape velocity: 5.0 km/s
- Orbital eccentricity: 0.0934
- Obliquity: 25°
- Orbit Inclination: 1.85°
- Visual Geometric Albedo: 0.15

Views of Mars



Schiparelli Hemisphere: This image is a mosaic of the Schiparelli hemisphere of Mars. This mosaic is composed of about 100 red and violet filter Viking Orbiter images. The images were acquired in 1980 during mid–northern summer on Mars. The center of this image is near the impact crater Schiaparelli, 450 kilometers in diameter.

The dark streaks with bright margins emanating from craters in the Oxie Palus region, upper left of image, are caused by erosion and/or deposition by the wind. Bright white areas to the south, including the Hellas impact basin at extreme lower right, are covered by carbon dioxide frost. *(Courtesy USGS).*

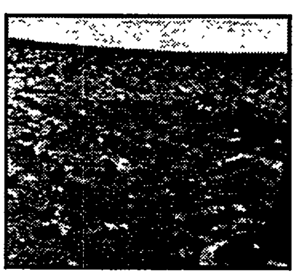

Valles Marineris: This image is a mosaic of the Valles Marineris hemisphere of Mars. It is a view similar to that which one would see from a spacecraft. The center of the scene shows the entire Valles Marineris canyon system, over 3,000 kilometers long and up to 8 kilometers deep, extending from Noctis Labyrinthus, the arcuate system of graben to the west, to the chaotic terrain to the east. Many huge ancient river channels begin from the chaotic terrain and north–central canyons and run north. Many of the channels flowed into a basin called Acidalia Planitia, which is the dark area in the extreme north of this picture. The three Tharsis volcanoes (dark red spots), each about 25 kilometers high, are visible to the west. South of Valles Marineris is very ancient terrain covered by many impact craters. *(Courtesy USGS).*


Olympus Mons: Olympus Mons is the largest volcano known in the solar system. It is classified as a shield volcano, similar to volcanoes in Hawaii. The central edifice of Olympus Mons has a summit caldera 24 km above the surrounding plains. Surrounding the volcano is an outward–facing scarp 550 km in diameter and several kilometers high. Beyond the scarp is a moat filled with lava, most likely derived from Olympus Mons. Farther out is an aureole of characteristically grooved terrain, just visible at the top of the frame. *(Courtesy NASA/JPL).*

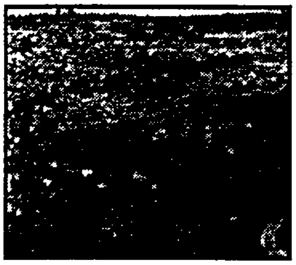

3D Olympus Mons: This 3D image of Olympus Mons was created from several images taken from different spacecraft positions and combined with a computer model of the surface topography. The final mosaic shows Olympus as it would be seen from the northeast. It is possible that volcanoes of such magnitude were able to form on Mars because the hot volcanic regions in the mantle remained fixed relative to the surface for hundreds of millions of years. *(Courtesy NASA/JPL).*

South Polar Cap: This image shows the south polar cap of Mars as it appears near its minimum size (about 400 km). It consists mainly of frozen carbon dioxide. This carbon dioxide cap never melts completely. The ice appears reddish due to dust that has been incorporated into the cap. *(Courtesy NASA).*

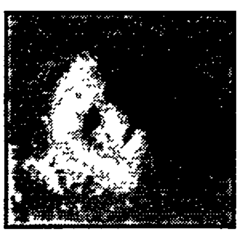
Lander 1 Site: Big Joe, the large rock just left of center is about 2 m (7 ft) wide. The top of the rock is covered with red soil. The exposed portions of the rock are similar in color to basaltic rocks on Earth. This rock may be a fragment of a lava flow that was later ejected by an impact crater. The red color of the rocks and soil is due to oxidized iron in the eroded material. In some areas of this scene rocky plains tend to dominate, while a short distance away drifts of regolith have formed. *(Courtesy NASA/JPL).*



Lander 2 Site: Viking Lander 2 used its sampler arm to dig these two trenches in the regolith. The shroud that protected the soil collector head during the lander's descent lies a short distance away. The lander's footpad is visible in the lower right corner of the image. The rounded rock in the center foreground is about 20 cm (8 in) wide, while the angular rock farther back and to the right is about 1.5 m (5 ft) across. The gently sloping troughs between the artificial trenches and the angular rock, which cut from the middle left to the lower right corner, are natural surface features. *(Courtesy NASA/JPL).*


View From Lander 1: The Viking Lander 1 site in Chryse Planitia is a barren desert with rocks strewn between sand dunes. The lander's footpad is visible at lower right; a trench in the foreground (just below center) was dug by the sampler arm. Patches of drift material and possibly bedrock are visible farther from the Lander. *(Courtesy NASA/JPL).*


View From Lander 2: The Viking Lander 2 site in Utopia Planitia has more and larger blocks of stone than does the Viking Lander 1 site in Chryse Planitia. The stones are probably ejecta from impact craters near the Lander 2 site. Many of the rocks are angular and are thought to be only slightly altered by the action of wind and other forms of erosion. Drifts of sand and dust are smaller and less noticable at the Lander 2 site. The overall red coloring of the Martian terrain is due to the presence of oxidized iron in the regolith. The pink color of the sky is caused by extremely fine red dust that is suspended in Mars' thin atmosphere. *(Courtesy NASA/JPL).*


Face on Mars: This image shows the *Face on Mars* that imaginative writers have cited as evidence for intelligent life on Mars. It is more likely that this hill, in the northern plains, has been eroded by the wind to give it a face like appearence.

Mars Moon Summary

The following table summarizes the radius, mass and distance from the planet center of each of the moons of Mars:

Moon	Radius	Mass	Distance
Phobos	14x10 km	1.08x10^16 kg	9,380 km
Deimos	8x6 km	1.8x10^15 kg	23,460 km

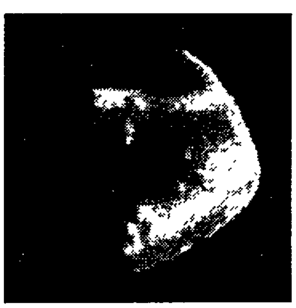
 **Deimos**

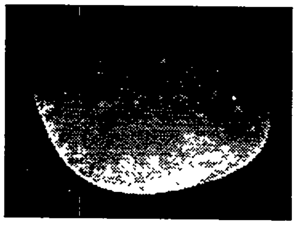
Deimos (panic) is a moon of Mars and was named after an attendant of the Roman war god Mars. Deimos is a dark body appearing to be composed of C–type surface materials. It is similar to the C–type (blackish carbonaceous chondrite) asteroids that are formed in the outer asteroid belt. It is speculated that Phobos, also a moon of Mars, and Deimos are captured asteroids; however, there are also arguments that go against this theory. Both Phobos and Deimos are saturated with craters. Deimos has a smoother appearance caused by partial filling of some of its craters.

Deimos Statistics

- Radius: 8 x 6 km
- Mass: 1.8 x 10^15 kg
- Density: 1.7 gm/cm^3
- Distance from Mars: 23,460 km
- Orbital period: 1.263 days
- Orbital inclination: 0.9–2.7°
- Orbital eccentricity: 0
- Magnitude (Vo): 12.4

Views of Deimos

 **Deimos:** This image was taken by the Viking Orbiter spacecraft in 1977.



Mosaic of Deimos: Measuring 16 by 12 km (10 by 7.5 mi) Deimos circles Mars every 30 hours. Craters of varying age dot its surface, which is somewhat smoother than the surface of Phobos. *(Courtesy NASA/JPL).*

Solar System Home

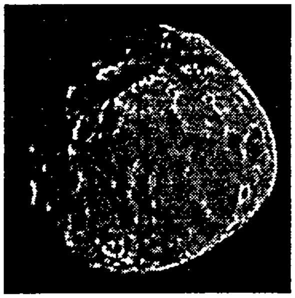
Phobos

Phobos (fear) is a moon of Mars and was named after an attendant of the Roman war god Mars. Phobos is a dark body appearing to be composed of C–type surface materials. It is similar to the C–type (blackish carbonaceous chondrite) asteroids that are formed in the outer asteroid belt. It is speculated that Phobos and Deimos are captured asteroids; however, there are also arguments that go against this theory. Phobos shows striated patterns which are probably cracks caused by the impact event of the largest crater on the moon.

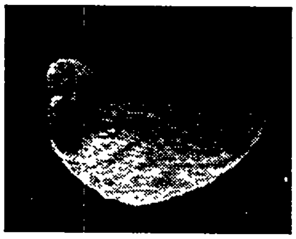
Phobos Statistics

- Radius: 14 x 10 km
- Mass: 1.08 x 10^16 kg
- Density: 2.0 gm/cm^3
- Distance from Mars: 9,380 km
- Orbital period: 0.319 days
- Orbital inclination: 1.0°
- Orbital eccentricity: 0.01
- Magnitude (Vo): 11.3

Views of Phobos

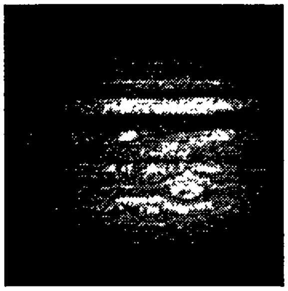


Phobos: This image was taken by the Viking Orbiter spacecraft in 1977. Striated patterns can be seen in this image. These are probably cracks caused by the impact event of the Stickney crater shown below.



Stickney Crater: One of the most striking features of Phobos, aside from its irregular shape, is its giant crater Stickney. Only 28 by 20 km (17 by 12 mi), Phobos must nearly have shattered from the force of the impact that caused the giant crater. Grooves that extend across the surface from Stickney appear to be surface fractures caused by the impact. Near the crater the grooves measure about 700 m (2300 ft) across and 90 m (295 ft) deep. However, most of the grooves have widths and depths in the 100 to 200 m (328 to 655 ft) and 10 to 20 m (33 to 65 ft) ranges, respectively. *(Courtesy NASA/JPL).*

Solar System Home



Jupiter

Hyper–links to Jupiter's Moons:

Adrastea, Amalthea, Ananke, Callisto, Carme, Elara, Europa, Ganymede, Himalia, Io, Leda, Lysithea, Metis, Pasiphae, Sinope, and Thebe.

Net Resources For Jupiter:

- Raw Voyager Images of Jupiter.
- Local Images of the Comet Impact on Jupiter
- Shoemaker–Levy 9/Jupiter Collision Information & Images
- Comet Shoemaker–Levy 9 Impact from JPL

Chronology of Jupiter Exploration

Jupiter is the fifth planet from the sun and is the largest one in the solar system. If Jupiter were hollow it could fit over a thousand Earths within itself. It also contains more matter than all of the other planets combine. It has a mass of 1.9 x 10^{27} kg and is 142,800 km (88,240 mi) across the equator. Jupiter possess 16 satellites. Four of which were even observed by Galileo as long ago as 1610. There is a ring system but it is very faint and is totally invisible from the Earth. The atmosphere is very deep, perhaps comprising the whole planet and is somewhat like the sun. It is composed mainly of hydrogen and helium, with small amounts of methane, ammonia, water vapor and other compounds. At great depths, within Jupiter, the pressure is so great that the hydrogen atoms are broken up and the electrons are freed so that the resulting atoms consist of bare protons. This produces a state in which the hydrogen becomes metallic.

Colorful latitudinal bands and atmospheric clouds and storms illustrate Jupiter's dynamic weather systems. The cloud patterns change constantly within hours and days. The Great Red Spot is a complex storm moving in a counterclockwise direction. An array of other smaller storms and eddies can be found through out the banded clouds.

Jupiter Rings

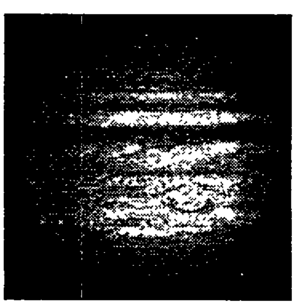
Unlike Saturn's intricate and complex ring patterns, Jupiter has a single ring that is almost uniform in its structure. It is probably composed of dust grains which extend to an outer edge of 129,000 km (80,000 miles) from the center of the planet and inward to about 30,000 km (18,000 miles). The origin of the ring is probably from micrometeorite bombardment of the tiny moons orbiting within the ring.

Jupiter's rings and moons exist within an intense radiation belt of electrons and ions trapped in the planet's magnetic field. These particles and fields comprise the jovian magnetosphere or magnetic environment, which extends 3 to 7 million kilometers toward the Sun, and stretches in a windsock shape at least as far as Saturn's orbit – a distance of 750 million kilometers (460 million miles).

Jupiter Statistics

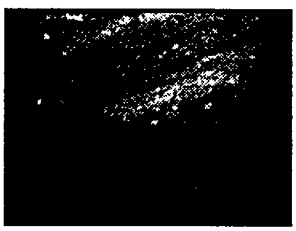
- Mean distance from the Sun: 5.203 AU (7.7833 x 10^8 km)
- Polar radius: 66770 km
- Equatorial radius: 71398 km
- Mass: 1.901 x 10^27 kg
- Mean density: 1.33 gm/cm^3
- Rotational Period: 9.841 hours
- Orbital period: 11.9 years
- Mean orbital velocity: 13.06 km/s
- Equatorial surface gravity: 22.88 m/s^2
- Equatorial escape velocity: 59.6 km/s
- Orbital eccentricity: 0.0483
- Obliquity: 3.08°
- Orbit Inclination: 1.308°
- Visual Geometric Albedo: 0.44

Views of Jupiter



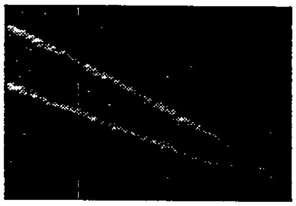
Jupiter: This image was taken by the Wide Field/Planetary Camera of the Hubble telescope. It is a true color composite of the full disk of Jupiter. All features in this image are cloud formations in the Jovian atmosphere, which contain small crystals of frozen ammonia and traces of colorful compounds of carbon, sulfur and phosphorous. This photograph was generated using three separate WFPC exposures in red, green and blue light on 28th May, 1991. It is part of a sequence of 45 exposures which were taken during an interval of 32 hours through five different colored filters as part of an ongoing study of the dynamic cloud and wind systems on Jupiter. *(Courtesy NASA/JPL).*

Nordic Optical Telescope: This image of Jupiter was taken with the 2.6 m Nordic Optical Telescope, located at La Palma, Canary Islands. It is a good example of the best imagery that can be obtained from earth based telescopes. (c) Nordic Optical Telescope Scientific Association (NOTSA).



Jupiter and Moons: Voyager 1 took this photo of Jupiter and two of its satellites (Io left and Europa right) on Feb. 13, 1979. In this view, Io is about 350,000 kilometers (220,000 miles) above Jupiter's Great Red Spot, while Europa is about 600,000 kilometers (375,000 miles) above Jupiter's clouds. Jupiter is about 20 million kilometers (12.4 million miles) from the spacecraft at the time of this photo. At this resolution (about 400 kilometers or 250 miles) there is evidence of circular motion in Jupiter's atmosphere. While the dominant large scale motions are west–to–east, small scale movement includes eddy like circulation within and between the bands. *(Courtesy NASA/JPL)*

The Great Red Spot: This dramatic view of Jupiter's Great Red Spot and its surroundings was obtained by Voyager 1 on Feb. 25, 1979, when the spacecraft was 5.7 million miles (9.2 million kilometers) from Jupiter. Cloud details as small as 100 miles (160 kilometers) across can be seen here. The colorful, wavy cloud pattern to the left of the Red Spot is a region of extraordinarily complex and variable wave motion. *(Courtesy NASA/JPL).*

**Ring of Jupiter:** The ring of Jupiter was discovered by Voyager 1 in March of 1979. This image was taken by Voyager 2 and has been pseudo colored. The Jovian ring is about 6500 km wide and probably less than 10 km thick.

**Equator of Jupiter:** This image shows the entire equatorial region of Jupiter. It was created by mosaicking several images together. The *Great Red Spot* is towards the left of the image. *(Courtesy NASA/JPL)*

Rings of Jupiter

Name	Distance*	Width	Thickness	Mass	Albedo
Halo	100,000 km	22,800 km	20,000 km	?	0.05
Main	122,800 km	6,400 km	< 30 km	1 x 10^13 kg	0.05
Gossamer	129,200 km	850,000 km	?	?	0.05

*The distance is measured from the planet center to the start of the ring.

Jupiters Moon Summary

Sixteen moons have been discovered orbiting around Jupiter. Most of them are relatively small and seem to have been more likely captured than to have been formed in orbit around Jupiter. Four of the largest moons, Io, Europa, Ganymede and Callisto, are believed to have accreted as part of the process by which Jupiter itself formed. The following table summarizes the radius, mass and distance from the planet center of each of the moons of Jupiter:

Moon	Radius	Mass	Distance
Metis	20 km	?	127,960 km
Adrastea	12x10x7 km	?	128,980 km
Amalthea	135x83x75 km	?	181,300 km
Thebe	55x45 km	?	221,900 km
Io	1,815 km	8.94x10^22 kg	421,600 km
Europa	1,569 km	4.8x10^22 kg	670,900 km
Ganymede	2,631 km	1.48x10^23 kg	1,070,000 km
Callisto	2,400 km	1.08x10^23 kg	1,883,000 km
Leda	8 km	?	11,094,000 km

Himalia	90 km	?	11,480,000 km
Lysithea	20 km	?	11,720,000 km
Elara	40 km	?	11,737,000 km
Ananke	15 km	?	21,200,000 km
Carme	22 km	?	22,600,000 km
Pasiphae	35 km	?	23,500,000 km
Sinope	20 km	?	23,700,000 km

Solar System Home

Voyage to Saturn

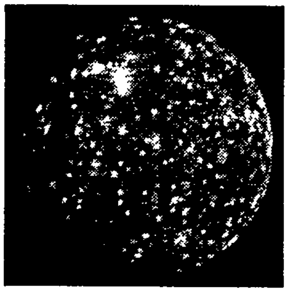
Amalthea

Amalthea is one of Jupiter's smaller moons. It is extremely irregular, having dimensions of about 270x165x150 km. It is heavily scarred by craters some being extremely large relative to the size of the moon. One such crater measures 90 km across and another 75 km across. The surface has a redish color apparently due to a dusting of sulphur originating from Io.

Amalthea Statistics

- Radius: 135 x 75 km
- Mass: ?
- Density: ?
- Distance from Jupiter: 181,300 km
- Orbital period: 0.498 days
- Orbital inclination: 0.4°
- Orbital eccentricity: 0
- Magnitude (Vo): 14.1

Solar System Home



Callisto

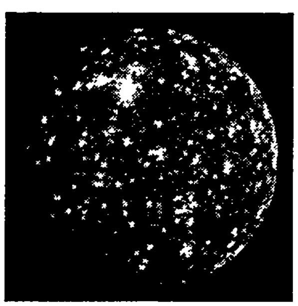
Callisto is the second largest moon of Jupiter. It has no atmosphere and is about the same size as Mercury . It is composed of approximately equal proportions of ice–water and rock. Its crust is very old and heavily cratered with remnant rings of enormous impact craters. The largest craters have been erased by the flow of the icy crust over geologic time. Craters and the associated concentric rings are about the only features to be found on Callisto.

The moon is probably composed of a large rocky core surrounded by water and ice giving it a dark color. Meteorites have punctured holes in the crust causing water to spread over the surface forming bright rays and rings around the crater.

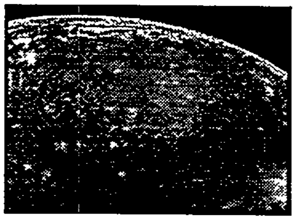
Callisto Statistics

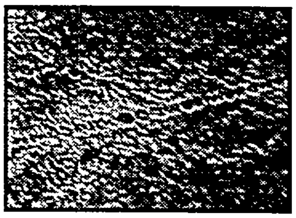
- Radius: 2400 km
- Mass: 1.08 x 10^23 kg
- Density: 1.86 gm/cm^3
- Distance from Jupiter: 1,883,000 km
- Orbital period: 16.689 days
- Orbital inclination: 0.28°
- Orbital eccentricity: 0.01
- Magnitude (Vo): 5.6

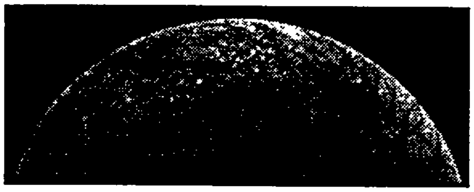
Views of Callisto



Callisto: This image of shows the heavely cratered surface of Callisto It was taken by Voyager 2 on July 7, 1979. Towards the top and slightly left of center is an enormous impact basin with concentric rings extending out from it.


Callisto's Valhalla Region: This close up of Callisto shows the heavely cratered surface and the prominant ring structure known as Valhalla. It was acquired by Voyager 1 on March, 6 1979. Valhalla's bright central area is about 300 km across with sets of concentric ridges extending out to 1,500 km from the center.


Gipul Catena: This image of an chain of craters on Callisto is 620 kilometers long. The largest crater is 40 kilometers across. This is the longest of 12 or so such chains on Callisto. The chain probably formed from the collision of a comet that was tidally disrupted during close passage of Jupiter such as the comet Shoemaker–Levy 9.

 Europa

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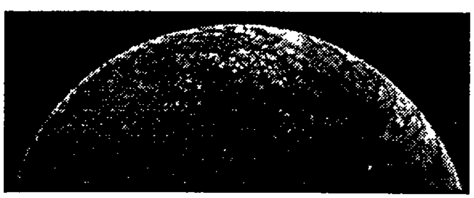
Europa is a strange looking moon of Jupiter with a large number of intersecting features. It is unlike Callisto and Ganymede with their heavily cratered crusts. Europa has almost a complete absence of craters as well as almost no vertical relief. This implies that it has a thin crust of water–ice less than 30 km (18 miles) thick, perhaps floating on a 50 km deep (30 mile) ocean. The visible markings could be a result of global expansion where the crust could have fractured and then filled with water and froze. Europa may be internally active due to tidal heating.

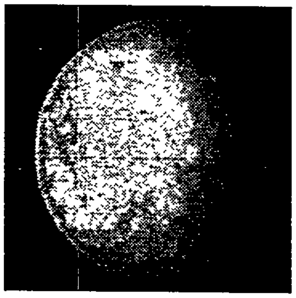
Europa Statistics

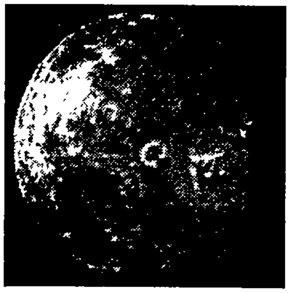
- Radius: 1569 km
- Mass: 4.8 x 10^22 kg
- Density: 2.97 gm/cm^3
- Distance from Jupiter: 670,900 km
- Orbital period: 3.551 days
- Orbital inclination: 0.47°
- Orbital eccentricity: 0.01
- Magnitude (Vo): 5.3

Views of Europa



Europa: This is one of the highest resolution images of Europa obtained by Voyager 2. It shows the smoothness of most of the terrain and the near absence of impact craters. Only three craters larger than 5 km in diameter have been found.

 **Europa From a Distance:** This view of Europa was taken by Voyager 2 and shows a bright, low–contrast surface with a network of lines which crisscross much of its surface.

 Io

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Io can be classified as one of the most unusual moons in our solar system. Active volcanism on Io was the greatest unexpected discovery at Jupiter. It was the first time active volcanoes had been seen on another body in the solar system. The Voyagers observed the eruption of nine volcanoes on Io altogether. There is also evidence that other eruptions occurred between Voyager encounters. Plumes from the volcanos extend to more than 300 kilometers (190 miles) above the surface with material being ejected at speeds up to a kilometer per second.

Io's volcanoes are apparently due to heating of the satellite by tidal pumping. Io is perturbed in its orbit by Europa and Ganymede, two other large satellites nearby, then pulled back again into its regular orbit by Jupiter. This tug–of–war results in tidal bulging as great as 100 meters (330 feet) on Io's surface.

Io is composed primarily of rocky material with very little iron. Io is located within an intense radiation belt of electrons and ions trapped in Jupiter's magnetic field. As the magnetosphere rotates with Jupiter, it sweeps past Io and strips away about 1,000 kilograms (1 ton) of material per second. The material forms a torus, a doughnut shaped cloud of ions that glow in the ultraviolet. The torus's heavy ions migrate outward, and their pressure inflates the jovian magnetosphere to more than twice its expected size. Some of the more energetic sulfur and oxygen ions fall along the magnetic field into the planet's atmosphere, resulting in auroras.

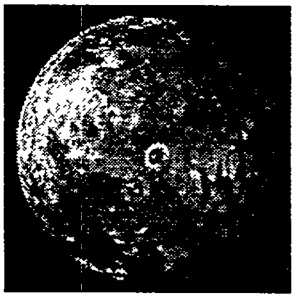
Io acts as an electrical generator as it moves through Jupiter's magnetic field, developing 400,000 volts across its diameter and generating an electric current of 3 million amperes that flows along the magnetic field to the planet's ionosphere.

Io Statistics

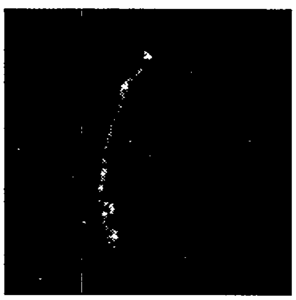
- Radius: 1815 km
- Mass: 8.94 x 10^22 kg
- Density: 3.57 gm/cm^3
- Distance from Jupiter: 412,600 km
- Orbital period: 1.769 days

- Rotational period: 1.769 days
- Orbital inclination: 0.04°
- Orbital eccentricity: 0
- Magnitude (Vo): 5.0

Views of Io



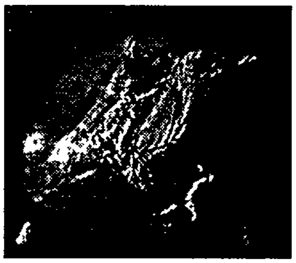
Io: Voyager 1 took this picture of Io on March 4, 1979. The brown, orange areas are probably covered by sulphur of a mixture containing sulphur. The light areas may be sulphur dioxide snow and the pock–marks are mostly volcanic calderas up to 200 km across. Mountainous regions exist near both poles, with some features rising 8 km or more above their surroundings.



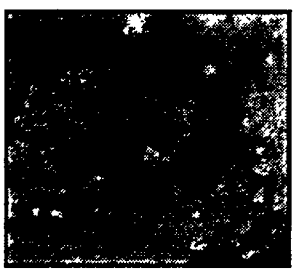
Volcanic Plumes: Voyager 2 took this picture of Io on the evening of July 9, 1979, from a range of 1.2 million kilometers. On the limb of Io are two blue volcanic eruption plumes about 100 kilometers high. These two plumes were first seen by voyager 1 in March 1979 and are designated Plume 5 (upper) and Plume 6 (lower). They have apparently been erupting for a period of at least four months and probably longer. A total of six plumes have been seen by voyager 2, all of which were first seen by Voyager 1. The largest plume viewed by Voyager 1, Plume 1, is no longer erupting. Plume 4 was not viewed on the edge of Io's disc by Voyager 2 and therefore it is not known whether or not it is still erupting. *(Courtesy NASA/JPL).*

Loki Volcano: Voyager 1 took this picture of the Loki volcano on March 4, 1979. The volcanic erruption can be seen on the limb of Io.

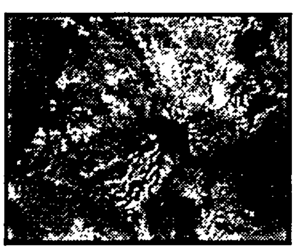
Loki Patera: This is a close up view of the surface of Io in the northern hemisphere. The central feature has been named *Loki Patera.* The large dark area may be a lake of liquid sulfer with a *raft* of solid sulfer inside.



Haemus Mons: Haemus Mons is a mountain located near the south pole and in this image near the terminator of Io. Its base measures about 200 by 100 km. Several mountain peaks are found on Io some measuring as high as 10 km tall.



Volcano Pele: The heart shapped feature in the center of this image was caused by volcanic ejecta thrown out the erruptive Pele.



Another View of Io:

Solar System Home

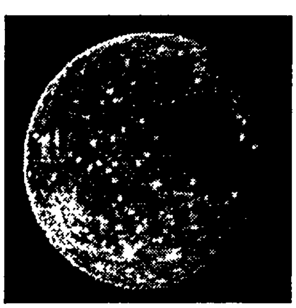
Ganymede

Ganymede is the largest moon of Jupiter and is the largest in our solar system with a diameter of 5,262 km (3,280 miles). Like Callisto, Ganymede is most likely composed of a rocky core with a water/ice mantle and a crust of rock and ice. It has no known atmosphere. Ganymede is mottled by both light and dark regions. It is heavily cratered especially in the dark regions implying ancient origin. The bright regions show a different kind of terrain -- one which is groved with ridges and troughs. These features form complex patterns and have a vertical relief of a few hundred meters and run for thousands of kilometers. The groved features were apparently formed more recently than the dark cratered area perhaps by tension from global tectonic processes. The real reason is unknown; however, local crust spreading does appear to have taken place causing the crust to shear and separate.

Ganymede Statistics

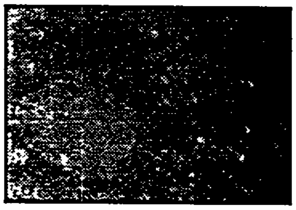
- Radius: 2631 km
- Mass: 1.48 x 10^23 kg
- Density: 1.94 gm/cm^3
- Distance from Jupiter: 1,070,000 km
- Orbital period: 7.155 days
- Orbital inclination: 0.19°
- Orbital eccentricity: 0
- Magnitude (Vo): 4.6

Views of Ganymede

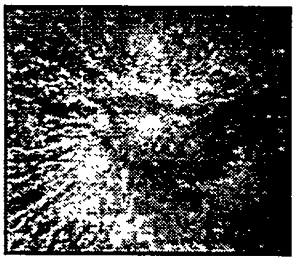


Ganymede: This shows an entire hemisphere of Ganymede. The prominant drak region, called Galileo Regio, is about 3,200 km in diameter.

The bright spots are relative recent impact craters. Part of the Galileo Regio may be covered with a bright frost.



Southern Galileo Regio: This image of southern Galileo Regio shows impact craters in various stages of degradation. Almost all of the craters appear flat. The two prominent light colored craters are almost completely erased by the flow in the icy crust.



Impact Crater (2,014,460 bytes): This mosaic of high resolution images on Ganymede shows a relative fresh impact basin surrounded by ejecta.

Saturn

Hyper–links to Saturn's Moons:

Atlas, Calypso, Dione, Enceladus, Epimetheus, Helene, Hyperion, Iapetus, Janus, Mimas, Pan, Pandora, Phoebe, Prometheus, Rhea, Telesto, Tethys, and Titan.

Net Resources For Saturn:

- Raw Voyager Images of Saturn.

Chronology of Saturn Exploration

Saturn is the sixth planet from the sun and is the second largest one in the solar system with an equatorial diameter of 74,130 mi (119,300 km). Much of what is known about the planet is due to the Voyager explorations in 1980–81. The planet is visibly flattened at the poles, a result of the very fast rotation of the planet on its axis. Its day is 10 hours 39 minutes and it takes 29.5 Earth years to rotate about the sun. The atmosphere is primarily composed of hydrogen with small amounts of helium and methane. Its density is about 70 percent that of water. Its hazy yellow hue is marked by broad atmospheric banding similar to but fainter than that found on Jupiter.

The most outstanding feature of Saturn is its ring system causing it to be considered one of the more beautiful objects in the sky. The rings are split into a number of different parts which include the bright A and B rings and a fainter C Ring. Within the ring system are various gaps. The most notable is that of the Cassini Division which separates the A and B rings. The Cassini Division was discovered by Giovanni Cassini in 1675. The A ring is also split by the Encke Division named after Johann Encke in 1837. Space probes have shown that the main rings are really made up of a large number of narrow ringlets. The origin of the rings is obscure. It is thought that the rings may have been formed from larger moons that were shattered by impacts of comets and meteoroids. The ring composition is not known for certain but they do show a significant amount of water. They may be composed of icebergs and/or snowballs from a few centimeters in size to a few meters in size. Much of the elaborate structure of some of the rings is due to the gravitational effects of nearby satellites. This phenomenon is demonstrated by the relationship between the F–ring and two small moons that "shepherd" the ring material.

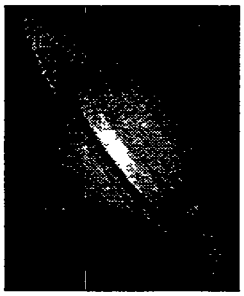
Radial, spoke like features in the broad B–ring were also found by the voyagers. The features are believed to be composed of fine, dust–size particles. The spokes were observed to form and dissipate in the time–lapse images taken by the Voyagers. While electrostatic charging may create spokes by levitating dust particles above the ring, the exact cause of the formation of the spokes is not well understood.

Saturn has the largest number of satellites in the solar system, over 18.

Saturn Statistics

- Mean distance from the Sun: 9.54 AU (1.42698 x 10^9 km)
- Polar radius: 49,000 km
- Equatorial radius: 60,000 km
- Mass: 5.688 x 10^26 kg
- Mean density: 0.69 gm/cm^3
- Rotational Period: 10.233 hours
- Orbital period: 29.5 years
- Mean orbital velocity: 9.64 km/s
- Equatorial surface gravity: 9.05 m/s^2
- Equatorial escape velocity: 35.5 km/s
- Orbital eccentricity: 0.0560
- Obliquity: 26.7°
- Orbit Inclination: 2.49°
- Visual Geometric Albedo: 0.46

Views of Saturn

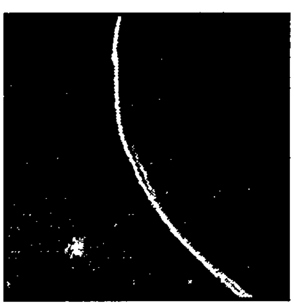


Saturn: NASA's Voyager 2 took this photograph of Saturn on July 21, 1981, when the spacecraft was 33.9 million kilometers (21 million miles) from the planet. Two bright, presumably convective cloud patterns are visible in the mid–northern hemisphere and several dark spoke–like features can be seen in the broad B–ring (left of planet). The moons Rhea and Dione appear as blue dots to the south and southeast of Saturn, respectively. Voyager 2 made its closest approach to Saturn on Aug. 25, 1981. *(Courtesy NASA/JPL).*

Nordic Optical Telescope: This image of Saturn was taken with the 2.6 m Nordic Optical Telescope, located at La Palma, Canary Islands. (c) Nordic Optical Telescope Scientific Association (NOTSA).

Rings of Saturn: This color–enhanced image shows the dark spoke–like features in the rings. The spokes seem to form very rapidly with sharp edges and then dissipate. The A ring appears as the outermost bands but in this image appears as two bands divided by the Encke's division. The Cassini's division divides the A and B bands.

Last View of Saturn: Two days after its encounter with Saturn, Voyager 1 looked back on the planet from a distance of more than 5 million km. This view of Saturn has never been seen by an earth based telescope, since the earth is so close to the sun only the sunlit face of Saturn can be seen.



Saturn's F Ring: Saturn's outermost ring, the F–ring, is a complex structure made up of two narrow, braided, bright rings along which "knots" are visible. Scientists speculate that the knots may be clumps of ring material, or mini moons. The F–ring was photographed at a range of 750,000 km (470,000 mi). *(Courtesy NASA/JPL).*

Rings of Saturn

The following is a summary of the rings of Saturn.

Name	Distance*	Width	Thickness	Mass	Albedo
D	67,000 km	7,500 km	?	?	?
C	74,500 km	17,500 km	?	1.1x10^18 kg	0.25
Maxwell Gap	87,500 km	270 km			
B	92,000 km	25,500 km	0.1-1 km	2.8x10^19 kg	0.65
Cassini Div	117,500 km	4,700 km	?	5.7x10^17 kg	0.30
A	122,200 km	14,600 km	0.1-1 km	6.2x10^18 kg	0.60
Encke gap	133,570 km	325 km			
Keeler gap	136,530 km	35 km			
F	165,800 km	30-500 km	?	?	?
G	165,800 km	8,000 km	100-1000 km	6-23x10^6 kg	?
E	180,000 km	300,000 km	1,000 km	?	?

*The distance is measured from the planet center to the start of the ring.

Saturns Moon Summary

The following table summarizes the radius, mass and distance from the planet center of each of the moons of Saturn:

Moon	Radius	Mass	Distance
Pan	9.655 km	?	133,000 km
Atlas	20x15 km	?	137,640 km
Prometheus	70x50x40 km	?	139,350 km
Pandora	55x45x40 km	?	141,700 km
Epimetheus	70x60x50 km	?	151,422 km
Janus	110x80 km	?	151,472 km
Mimas	195 km	3.8x10^19 kg	185,520 km
Enceladus	250 km	8.40x10^19 kg	238,020 km
Tethys	525 km	7.55x10^20 kg	294,660 km
Telesto	17x14x13 km	?	294,660 km
Calypso	17x11x11 km	?	294,660 km
Dione	560 km	1.05x10^21 kg	377,400 km
Helene	18x16x15 km	?	377,400 km
Rhea	765 km	2.49x10^21 kg	527,040 km
Titan	2,575 km	1.35x10^23 kg	1,221,850 km
Hyperion	205x130x110 km	?	1,481,000 km
Iapetus	720 km	1.88x10^21 kg	3,561,300 km
Phoebe	110 km	?	12,952,000 km

Solar System Home
Voyage to Uranus

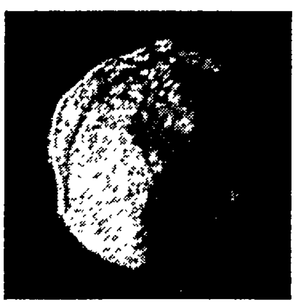
Saturn's Other Moons

This page contains images and statistics of Saturn's moons, Calypso, Epimetheus, Janus, Pandora, Phoebe and Telesto.

Calypso

Calypso Statistics

- Radius: 15x10 km
- Mass: ?
- Density: ?
- Distance from Saturn: 294,660 km
- Orbital period: 1.888 days
- Orbital inclination: 0°
- Orbital eccentricity: 0
- Magnitude (Vo): 19.0

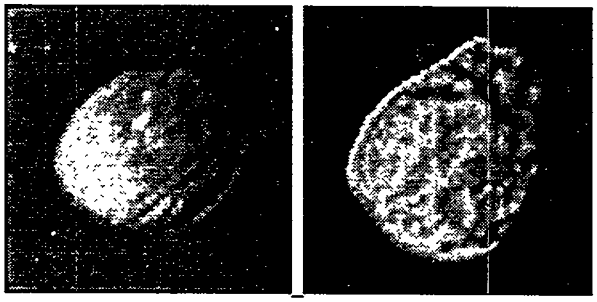


Epimetheus

Epimetheus Statistics

- Radius: 70 x 50 km
- Mass: ?
- Density: ?
- Distance from Saturn: 151,422 km
- Orbital period: 0.694 days

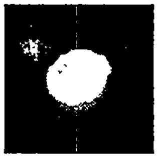
- Orbital inclination: 0.34°
- Orbital eccentricity: 0.01
- Magnitude (Vo): 15.7



Janus

Janus Statistics

- Radius: 110 x 80 km
- Mass: ?
- Density: ?
- Distance from Saturn: 151,472 km
- Orbital period: 0.695 days
- Orbital inclination: 0.14°
- Orbital eccentricity: 0.01
- Magnitude (Vo): 14.5



Pandora

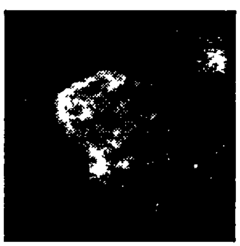
Pandora Statistics

- Radius: 55 x 35 km
- Mass: ?
- Density: ?
- Distance from Saturn: 141,700 km
- Orbital period: 0.629 days
- Orbital inclination: 0°
- Orbital eccentricity: 0
- Magnitude (Vo): 16.5

Phoebe

Phoebe Statistics

- Radius: 110 km
- Mass: ?
- Density: ?
- Distance from Saturn: 12,952,000 km
- Orbital period: 550.48 days
- Orbital inclination: 175.3°
- Orbital eccentricity: 0.16
- Magnitude (Vo): 16.5

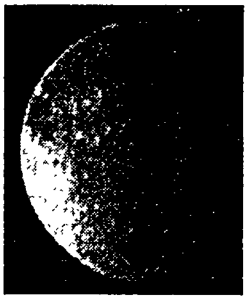


Telesto

Telesto Statistics

- Radius: 12 km
- Mass: ?
- Density: ?
- Distance from Saturn: 294,660 km
- Orbital period: 1.888 days
- Orbital inclination: 0°
- Orbital eccentricity: 0
- Magnitude (Vo): 18.7

Solar System Home



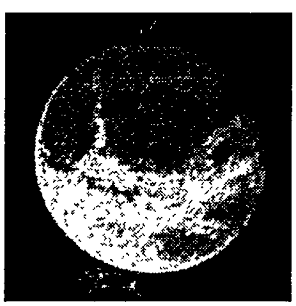
Dione

The three satellites Dione, Tethys and Rhea are all very similar in nature. They are all icy bodies. The density of Dione is 1.44 gm/cm^3 indicating that it has a rocky core making up 1/3 of the moons mass with the rest water–ice. Dione's icy surface is heavily cratered and has cracks caused by faults in the ice.

Dione Statistics

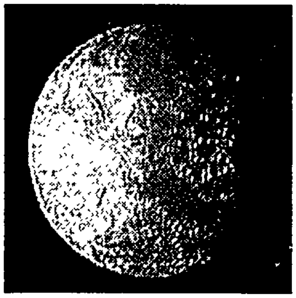
- Radius: 560 km
- Mass: 1.05 x 10^21 kg
- Density: 1.44 gm/cm^3
- Distance from Saturn: 377,400 km
- Orbital period: 2.737 days
- Orbital inclination: 0.02°
- Orbital eccentricity: 0
- Magnitude (Vo): 10.4

Views of Dione



This image is a color composite of Dione taken by Voyager 1 on November 12, 1980. It was constructed from three separate images taken through orange, green and blue filters. The wispy white streaks are perhaps deposits of snow exuded from fractures in its crust.

Solar System Home



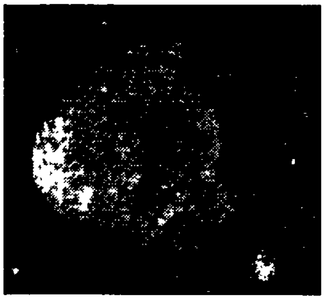
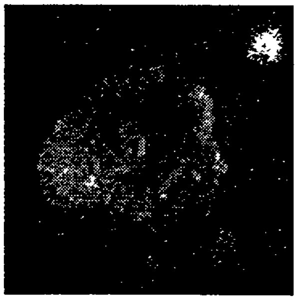
Enceladus

Enceladus is one of the innermost moons of Saturn. It is quite similar in size to Mimas but has a smoother, brighter surface. Unlike Mimas, Enceladus displays at least five different types of terrain. Parts of Enceladus shows craters no larger than 35 km in diameter. Other areas show regions with no craters indicating major resurfacing events in the geologically recent past. There are fissures, plains, corrugated terrain and other crustal deformations. All of this indicates that that interior of the moon may still be liquid today, even though it should have frozen aeons ago. It is postulated that Enceladus is heated by a tidal mechanism caused by perturbation by Saturns gravitations field and by the larger moons of Tethys and Dione nearby. Jupiter's moon Io is also perturbed in such a fashion.

Enceladus Statistics

- Radius: 250 km
- Mass: 8.40 x 10^19 kg
- Density: 1.24 gm/cm^3
- Distance from Saturn: 238,020 km
- Orbital period: 1.370 days
- Orbital inclination: 0.02°
- Orbital eccentricity: 0
- Magnitude (Vo): 11.7

Solar System Home

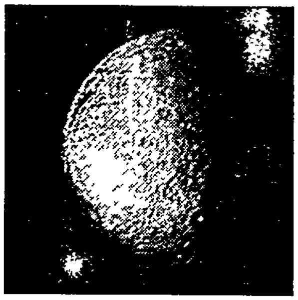
Hyperion

Hyperion is one of the smaller moons of Saturn. It has a pock–marked body and is irregularly shaped. Hyperion may have had a major collision which blew part of the moon away. Its eccentric orbit makes it subject to gravitational forces from Saturn which have set it tumbling out of control. Its rotational period is not constant and varies from one orbit to the next.

Hyperion Statistics

- Radius: 175 x 100 km
- Mass: ?
- Density: ?
- Distance from Saturn: 1,481,000 km
- Orbital period: 21.277 days
- Orbital inclination: 0.43°
- Orbital eccentricity: 0.1
- Magnitude (Vo): 14.2

Solar System Home

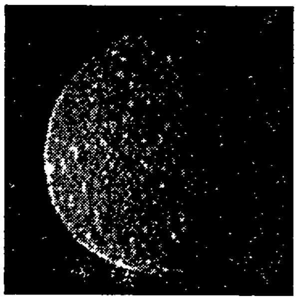
Iapetus

Iapetus is one of the stranger moons of Saturn. Its leading side is dark with a slight redish color while its trailing side is bright. The dark surface may have been matter swept up from space or it may have oozed from its inside. The real reason is still unknown. The dark material may be a thin layer of organic material perhaps similar to the complex substances found in the most primitive meteorites.

Iapetus Statistics

- Radius: 720 km
- Mass: 1.88 x 10^21 kg
- Density: 1.21 gm/cm^3
- Distance from Saturn: 3,561,300 km
- Orbital period: 79.331 days
- Orbital inclination: 14.72°
- Orbital eccentricity: 0.03
- Magnitude (Vo): 10.2–11.9

Solar System Home

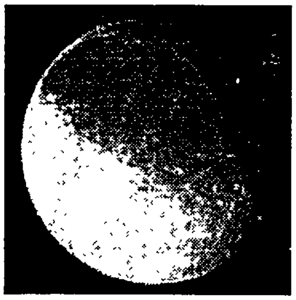
Mimas

Mimas is one of the innermost moons of Saturn. It was discovered by William Herschel in 1789. The surface is icy and heavily cratered. Due to its low density, Mimas probably consists primarily of ice. Since Mimas has such a low temperature (about –200° C), the impact features may date back to the time of the moons creation. One of the craters is surprisingly large in comparison to the size of the moon. This impact probably came close to disintegrating the moon. Traces of fracture marks can be seen on the opposite side of Mimas.

Mimas Statistics

- Radius: 195 km
- Mass: 3.8 x 10^19 kg
- Density: 1.17 gm/cm^3
- Distance from Saturn: 185,520 km
- Orbital period: 0.942 days
- Orbital inclination: 1.53°
- Orbital eccentricity: 0.02
- Magnitude (Vo): 12.9

Solar System Home



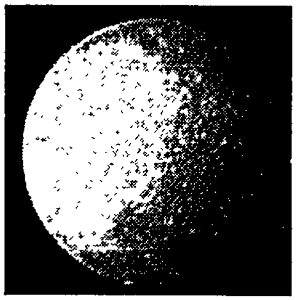
Rhea

The three satellites Dione, Tethys and Rhea are all very similar in nature. They are all icy bodies. The density of Rhea is 1.33 gm/cm^3 indicating that it has a rocky core making up less than 1/3 of the moons mass with the rest water–ice. Rhea's icy surface is totally saturated with craters. On the average, new impact events erase as many old craters as new ones are created.

Rhea's Statistics

- Radius: 765 km
- Mass: 2.49 x 10^21 kg
- Density: 1.33 gm/cm^3
- Distance from Saturn: 527,040 km
- Orbital period: 4.518 days
- Orbital inclination: 0.35°
- Orbital eccentricity: 0
- Magnitude (Vo): 9.7

Solar System Home



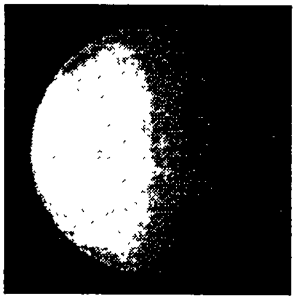
Tethys

The three satellites Tethys, Dione and Rhea are all very similar in nature. They are all icy bodies. The density of Tethys is 1.26 gm/cm^3 indicating that it is composed almost entirely of water–ice. Tethys's icy surface is heavily cratered and contains cracks caused by faults in the ice. There is one enormous trench on Tethys about 65 km wide and extending from above the center to the extreme left.

Tethys Statistics

- Radius: 525 km
- Mass: 7.55 x 10^20 kg
- Density: 1.26 gm/cm^3
- Distance from Saturn: 294,660 km
- Orbital period: 1.888 days
- Orbital inclination: 1.09°
- Orbital eccentricity: 0
- Magnitude (Vo): 10.2

Solar System Home



Titan

Titan is the largest moon of Saturn and the second largest moon in the solar system, rivaled only by Jupiter's moon Ganymede. Before the Voyager encounters, astronomers suspected that Titan might have some atmosphere of its own. Scientists also believed they might find liquid seas or pools of methane or ethane; water would be frozen due to Titan's low surface temperature. Expecting an unusual world, Voyager 1 was programmed to take numerous close up views of Titan as it flew past in November of 1980. Unfortunately, all that was revealed was an impenetrable layer of atmosphere and clouds. Only slight color and brightness variations were observed.

Although Titan is classified as a moon, it is larger than the planets Mercury and Pluto. It has a planet–like atmosphere which is more dense than those of Mercury, Earth, Mars and Pluto. Titan's air is predominantly made up of Nitrogen with other hydrocarbon elements which give Titan its orange hue. These hydrocarbon rich elements are the building blocks for amino acids necessary for the formation of life.

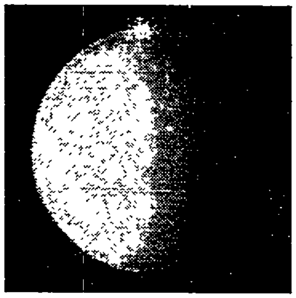
The Voyager spacecraft were not able to penetrate the thick layers of clouds but they did reveal that Titan is one of the more interesting places in the solar system. What kind of landscape lies below the layers of clouds? What mysteries are held beneath these orange curtains? These questions will have to wait until future spacecraft are launched to visit this unusual moon. In October of 1997, the Cassini spacecraft is planed to be launched for a rendezvous with Saturn in June 2004. Later that year it will release the European–built Huygens probe for a descent through Titan's atmosphere. Cassini will have more than 30 encounters with Titan in which radar will be used to map out its surface similar to the radar mapping of Venus by Magellan.

Titan Statistics

- Radius: 2,575 km
- Mass: 1.35 x 10^23 kg
- Density: 1.88 gm/cm^3
- Distance from Saturn: 1,221,850 km

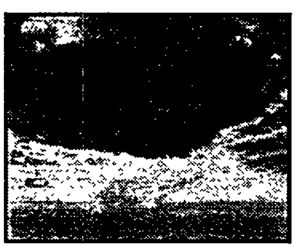
- Orbital period: 15.945 days
- Rotational period: 15.945 days
- Orbital inclination: 0.33°
- Orbital eccentricity: 0.03
- Magnitude (Vo): 8.3

Views of Titan

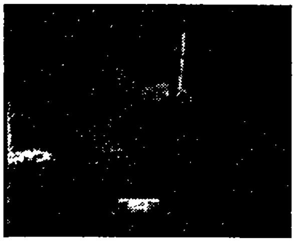


Titan: Opaque layers of clouds prevented Voyager from seeing Titan's surface during its 1980 flyby. The clouds over the southern hemisphere are lighter in color than over the northern hemisphere. There is a dark hood over the north pole.

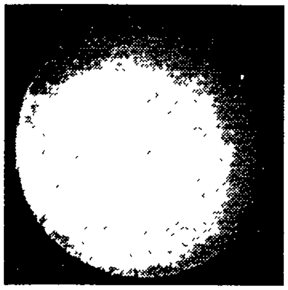
Titan Looking Back: This view of Titan was taken from a position looking almost directly back toward the sun. Titan's hydrocarbon–rich nitrogen atmosphere scatters sunlight in a forward direction over the limb around the entire disk. The surface of Titan is obscured due to a deep cloud layer. The only visible markings are the dark north polar hood and a difference in the brightness and color in the north and south hemispheres. *(Courtesy NASA/JPL).*



Huygens: This artist's rendering shows the European Space Agency's Huygens probe descending into the atmosphere of Saturn's moon Titan after being released by NASA's Cassini spacecraft. Planned for launch in October 1997, Cassini will reach Saturn in June 2004 and will release the Huygens probe later that year. *(Courtesy NASA/ESA).*



Huygens on Titan's Surface: This artist's rendering shows the Huygens probe on the surface of Saturn's moon Titan after being released by NASA's Cassini spacecraft. *(Courtesy NASA/ESA).*

 Uranus

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Hyper–links to Uranus' Moons:

Ariel, Belinda, Bianca, Cordelia, Cressida, Desdemona, Juliet, Miranda, Oberon, Ophelia, Portia, Puck, Rosalind, Titania, and Umbriel.

Net Resources For Uranus:

- Raw Voyager Images of Uranus.

Chronology of Uranus Exploration

Uranus is the seventh planet from the sun and is the third largest in the solar system. It was discovered by William Herschel in 1781. It has an equatorial diameter of 51,800 km (32,190 mi) and orbits the Sun once every 84.01 years. It has a mean distance from the sun of 2,869,600,000 km (1,783,135,000 mi). The length of a day on Uranus is 17 hours 14 minutes.

Uranus has at least 15 moons. Titania and Oberon are the largest two and were discovered by William Herschel in 1787.

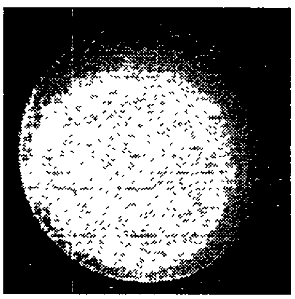
Uranus is distinguished by the fact that it is tipped on its side. Its unusual position is thought to be the result of a collision with a planet–sized body early in the solar system's history. Voyager 2 found that one of the most striking influences of this sideways position is its effect on the tail of the magnetic field, which is itself tilted 60 degrees from the planet's axis of rotation. The magnetotail was shown to be twisted by the planet's rotation into a long corkscrew shape behind the planet. The peculiar orientation of the magnetic field suggests that the field is generated at an intermediate depth in the interior where the pressure is high enough for water to become electrically conducting.

Uranus Statistics

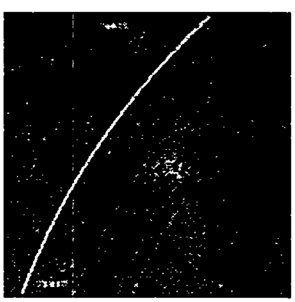
- Mean distance from the Sun: 19.1914 AU (2.87099 x 10^9 km)

- Equatorial radius: 25,559 km
- Mass: 8.684 x 10^25 kg
- Mean density: 1.29 gm/cm^3
- Rotational Period: 17.9 hours
- Orbital period: 84.01 years
- Mean orbital velocity: 6.81 km/s
- Equatorial surface gravity: 7.77 m/s^2
- Equatorial escape velocity: 21.3 km/s
- Orbital eccentricity: 0.0461
- Obliquity: 97.9°
- Orbit Inclination: 0.77°
- Visual Geometric Albedo: 0.56

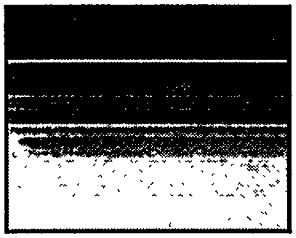
Views of Uranus



Uranus: This view of Uranus was acquired by Voyager 2 in January 1986. The greenish color of it atmosphere is due to methane and high–altitude photochemical smog.



Shepherd Satellites: The discovery of two shepherd satellites has advanced our understanding of the structure of the Uranian rings. The moons, designated 1986U7 and 1986U8, are seen here on either side of the bright epsilon ring; all 9 of the known Uranian rings are also visible. The epsilon ring appears surrounded by a dark halo as a result of image processing; occasional blips seen on the ring are also artifacts. Lying inward from the epsilon ring are the delta, gamma and eta rings; the beta and alpha rings; and finally the barely visible 4, 5 and 6 rings. The rings have been studied since their discovery in 1977. *(Courtesy NASA/JPL)*



Uranus' Rings: The 9 known rings of Uranus are visible here. The somewhat fainter, pastel lines seen between the rings are artifacts of computer enhancement. Six narrow–angle images were used to extract color information from the extremely dark and faint rings. The final image was made from three color averages and represents an enhanced, false–color view. The image shows that the brightest, or epsilon ring at top is neutral in color, with the fainter 8 remaining rings showing color differences between them. *(Courtesy NASA/JPL)*

Rings of Uranus

The following is a summary of the rings of Uranus.

Name	Distance*	Width	Thickness	Mass	Albedo
1986U2R	38,000 km	2,500 km	0.1 km	?	0.03
6	41,840 km	1-3 km	0.1 km	?	0.03
5	42,230 km	2-3 km	0.1 km	?	0.03
4	42,580 km	2-3 km	0.1 km	?	0.03
Alpha	44,720 km	7-12 km	0.1 km	?	0.03
Beta	45,670 km	7-12 km	0.1 km	?	0.03
Eta	47,190 km	0-2 km	0.1 km	?	0.03
Gamma	47,630 km	1-4 km	0.1 km	?	0.03
Delta	48,290 km	3-9 km	0.1 km	?	0.03
1986U1R	50,020 km	1-2 km	0.1 km	?	0.03
Epsilon	51,140 km	20-100 km	< 0.15 km	?	0.03

*The distance is measured from the planet center to the start of the ring.

Uranus Moon Summary

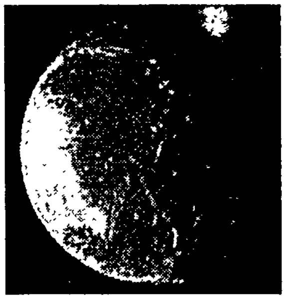
The following table summarizes the radius, mass and distance from the planet center of each of the moons of Uranus:

Moon	Radius	Mass	Distance
Cordelia	15 km	?	49,750 km
Ophelia	15 km	?	53,760 km
Bianca	20 km	?	59,160 km
Cressida	35 km	?	61,770 km
Desdemona	30 km	?	62,660 km
Juliet	40 km	?	64,360 km
Portia	55 km	?	66,100 km
Rosalind	30 km	?	69,930 km
Belinda	35 km	?	75,260 km
Puck	75 km	?	86,010 km

Miranda	235 km	6.89x10^19 kg	129,780 km
Ariel	580 km	1.26x10^21 kg	191,240 km
Umbriel	585 km	1.33x10^21 kg	265,970 km
Titania	790 km	3.48x10^21 kg	435,840 km
Oberon	760 km	3.03x10^21 kg	582,600 km

Solar System Home

Voyage to Neptune



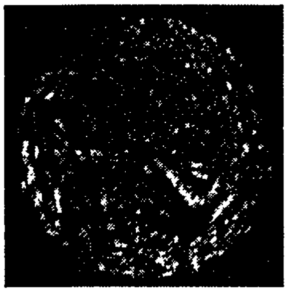
Ariel

Ariel [AIR–ee–ul] is a relatively small satellite and is the brightest moon of Uranus. The surface is pock–marked with craters, but the most outstanding features are long rift valleys stretching across the entire surface. Canyons much like the ones on Mars appear in the pictures. The canyon floors appear as though they have been smoothed by a fluid. If there was a fluid, it could not have been water since water acts like steel at these temperatures. Perhaps the flow marks could have been, ammonia, methane or even carbon monoxide.

Ariel Statistics

- Radius: 580 km
- Mass: 1.26 x 10^21 kg
- Density: 1.66 gm/cm^3
- Distance from Uranus: 191,240 km
- Orbital period: 2.52 days
- Orbital inclination: 0°
- Orbital eccentricity: 0
- Magnitude (Vo): 14.4

Solar System Home



Miranda

Miranda [mi–RAN–duh] is not one of the larger satellites of Uranus; however, it was the one that was approached the closest by Voyager 2. This was not the satellite scientists would have chosen to get close to if they had a choice, but they had no choice. Voyager 2 had to fly close to the planet in order to get the boost it needed to go to Neptune. The resolution at which the larger satellites were photographed was around 2 to 3 km. On the other hand, details on the order of a few hundred meters can be seen on Miranda. Fortunately, Miranda turned out to be the most remarkable of all the satellites.

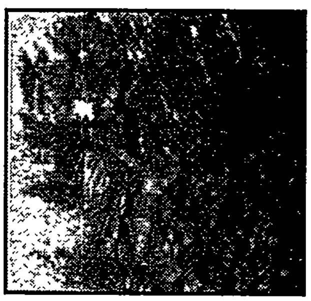
Miranda is a small satellite with a diameter of 470 km. Its surface is unlike anything in the solar system with features that are jumbled together in a haphazard fashion. Scientists believe that Miranda may have been shattered as many as five times during its evolution. After each shattering the moon would have reassembled form the remains of its former self with portions of the core exposed and portions of the surface buried. This is only a theory. The real reason why Miranda has its appearance is unknown.

Miranda Statistics

- Radius: 235 km
- Mass: 6.89 x 10^19 kg
- Density: 1.35 gm/cm^3
- Distance from Uranus: 129,780 km
- Orbital period: 1.414 days
- Orbital inclination: 3.4°
- Orbital eccentricity: 0
- Magnitude (Vo): 16.5

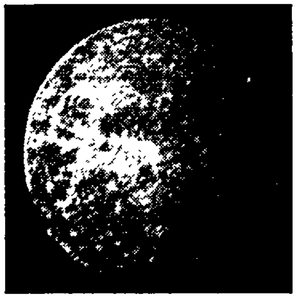
Views of Miranda

Miranda: Uranus' moon Miranda is shown in a computer–assembled mosaic of images obtained Jan. 24, 1986, by the Voyager 2 spacecraft. Miranda is the innermost and smallest of the five major Uranian satellites, just 480 kilometers (about 300 miles) in diameter. This image is a full–disc, south–polar view of the moon showing the varying geologic provinces of Miranda. Miranda's surface consists of two major strikingly different types of terrain. One is an old, heavily cratered, rolling terrain with relatively uniform albedo, or reflectivity. The other is a young, complex terrain characterized by sets of bright and dark bands, scarps and ridges. These are features found in the ovoid regions at right and left and in the distinctive *chevron* feature below and right of center.



The Chevron: This view of Miranda shows details as small as 600 meters across. It was acquired by Voyager 2 on January 24, 1986. This is a close–up view of the *chevron* which shows the light and dark grooves with its sharp boundaries. The upper right shows a region of uniformly dark grooved terrain. The area shown is about 150 km on a side.

Solar System Home



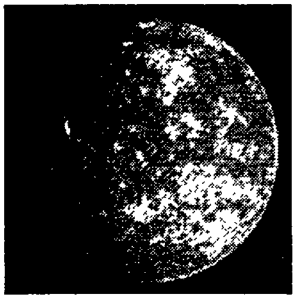
Oberon

Oberon [O–buh–ron] is a moon of Uranus that is characterized by many large impact craters across an icy surface. This image shows several large impact craters towards the center of the image. On the limb a high mountain rises 6 km above its surrounds. There are bright rays similar to those seen on Jupiter's moon Callisto.

Oberon Statistics

- Radius: 760 km
- Mass: 3.03 x 10^21 kg
- Density: 1.58 gm/cm^3
- Distance from Uranus: 582,600 km
- Orbital period: 13.463 days
- Orbital inclination: 0°
- Orbital eccentricity: 0
- Magnitude (Vo): 14.2

Solar System Home



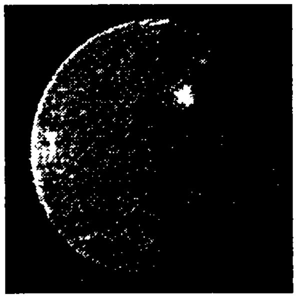
Titania

Titania [Ty–TAY–ne–ah] is the largest moon of Uranus. It is marked by a few large impact basins, but is generally covered with small craters and very rough rocks. The above image shows a thousand mile long trench. A large double walled crater can be seen towards the top of the image. There are many faults on Titania indicating there has been internal forces molding its surface.

Titania Statistics

- Radius: 790 km
- Mass: 3.48 x 10^21 kg
- Density: 1.68 gm/cm^3
- Distance from Uranus: 435,840 km
- Orbital period: 8.706 days
- Orbital inclination: 0°
- Orbital eccentricity: 0
- Magnitude (Vo): 14.0

Solar System Home



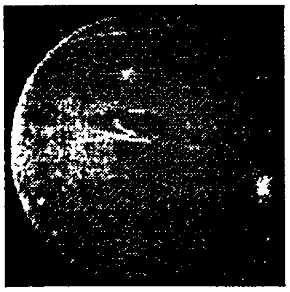
Umbriel

Umbriel [UM–bree–ul] is the darkest satellite of Uranus. It is about the same size as Ariel and has about the same density. The surface appears to be old with large craters and does not change much from one location to another. Near the top is a puzzling bright ring called the *fluorescent cheerio*. It is probably the floor of a crater.

Umbriel Statistics

- Radius: 585 km
- Mass: 1.33 x 10^21 kg
- Density: 1.51 gm/cm^3
- Distance from Uranus: 265,970 km
- Orbital period: 4.144 days
- Orbital inclination: 0°
- Orbital eccentricity: 0
- Magnitude (Vo): 15.3

Solar System Home

 **Neptune**

Hyper–links to Neptune's Moons:

Despina, Galatea, Larissa, Naiad, Nereid, Proteus, Thalassa, and Triton.

Net Resources For Neptune:

- Raw Voyager Images of Neptune.

Chronology of Neptune Exploration

Neptune is the outermost planet of the gas giants. It has an equatorial diameter of 49,500 km (30,760 mi). Neptune orbits the Sun every 165 years. It has eight moons, six of which were found by Voyager. A day on Neptune is 16 hours and 6.7 minutes.

The first two thirds of Neptune is composed of a mixture of molten rock, water, liquid ammonia and methane. The outer third is a mixture of heated gases comprised of hydrogen, helium, water and methane. Methane gives Neptune its blue cloud color.

Neptune is a dynamic planet with several large, dark spots reminiscent of Jupiter's hurricane–like storms. The largest spot, known as the *Great Dark Spot*, is about the size of the earth and is similar to the *Great Red Spot* on Jupiter. Voyager revealed a small, irregularly shaped, eastward–moving cloud *scooting* around Neptune every 16 hours or so. This *scooter* as it has been dubbed could be a plume rising above a deeper cloud deck.

Long bright clouds, similar to cirrus clouds on Earth, were seen high in Neptune's atmosphere. At low northern latitudes, Voyager captured images of cloud streaks casting their shadows on cloud decks below.

The strongest winds on any planet were measured on Neptune. Most of the winds there blow westward, opposite to the rotation of the planet. Near the Great Dark Spot, winds blow up to 2,000 kilometers (1,200 miles) an hour.

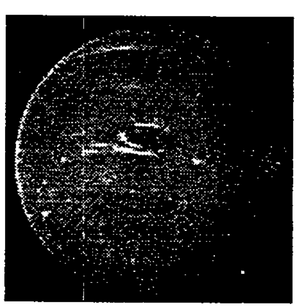
Neptune has a set of four rings which are narrow and very faint. The rings are made up of dust particles thought to have been made by tiny meteorites smashing into Neptunes moons. From ground based telescopes the rings appear to be arcs but from Voyager 2 the arcs turned out to be bright spots or clumps in the ring system. The exact cause of the bright clumps is unknown.

The magnetic field of Neptune, like that of Uranus, is highly tilted at 47 degrees from the rotation axis and offset at least 0.55 radii (about 13,500 kilometers or 8,500 miles) from the physical center. Comparing the magnetic fields of the two planets, scientists think the extreme orientation may be characteristic of flows in the interior of the planet and not the result of that planet's sideways orientation or of any possible field reversals at either planet.

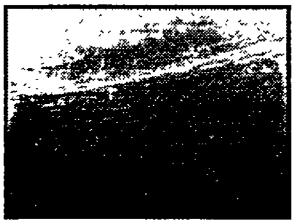
Neptune Statistics

- Mean distance from the Sun: 30.0611 AU (4.49707 x 10^9 km)
- Equatorial radius: 24,764 km
- Mass: 1.024 x 10^26 kg
- Mean density: 1.64 gm/cm^3
- Rotational Period: 19.2 hours
- Orbital period: 164.79 years
- Mean orbital velocity: 5.47 km/s
- Equatorial surface gravity: 11.0 m/s^2
- Equatorial escape velocity: 23.3 km/s
- Orbital eccentricity: 0.0097
- Obliquity: 29.6°
- Orbit Inclination: 1.77°
- Visual Geometric Albedo: 0.51

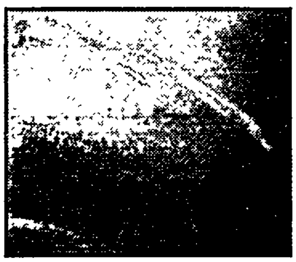
Views of Neptune


Neptune:

This picture of Neptune was taken by Voyager 2 on August 20th, 1989. One of the great cloud features can be seen toward the center of the image and has been dubbed by Voyager scientists the *Great Dark Spot*. It is at a latitude of 22 degrees south and circuits Neptune every 18.3 hours. The bright clouds to the south and east of the Great Dark Spot constantly change their appearances in periods as short as four hours.



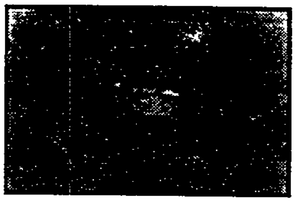
Cirrus–like Clouds: This image shows bands of sunlit cirrus–like clouds in Neptune's northern hemisphere. These clouds cast shadows on the blue cloud deck 35 miles below. The white streaky clouds are from 30 to 100 miles wide and extend for thousands of miles.



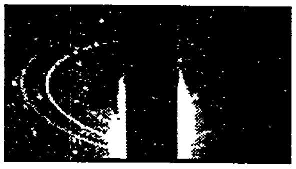
True–color Image

This Voyager 2 image has been processed by computers so that both the clouds' structure in the dark regions near the pole and the bright clouds east of the Great Dark Spot are visible. Small trails of clouds trending east to west and large–scale structure east of the Great Dark Spot all suggest that waves are present in the atmosphere and play a large role in the type of clouds that are visible. *(Courtesy NASA/JPL)*

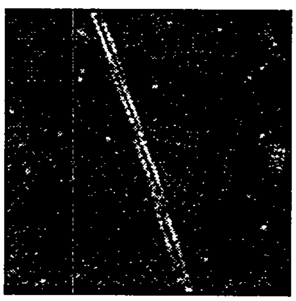
Great Dark Spot: Feathery white clouds fill the boundary between the dark and light blue regions on the Great Dark Spot. The pinwheel shape of both the dark boundary and the white cirrus suggests that the storm system rotates counterclockwise. Periodic small scale patterns in the white cloud, possibly waves, are short lived and do not persist from one Neptunian rotation to the next. *(Courtesy NASA/JPL)*



Small Dark Spot: This image shows the *Small Dark Spot* which is south of the *Great Dark Spot*. The small spot is thought to be a storm in Neptune's atmosphere, perhaps similar to Jupiter's Great Red Spot.



Neptune Rings: These two 591–second exposures of the rings of Neptune were taken by Voyager 2 on August 26, 1989 from a distance of 280,000 km. The two main rings are clearly visible and appear complete over the region imaged. Also visible in this image is the inner faint ring at about 42,000 kilometers (25,000 miles) from the center of Neptune, and the faint band which extends smoothly from the 53,000 kilometer (33,000 miles) ring to roughly halfway between the two bright rings. The bright glare in the center is due to over–exposure of the crescent of Neptune. Numerous bright stars are evident in the background. Both rings are continuous. *(Courtesy NASA/JPL)*



Twisted Rings: This portion of one of Neptune's rings appears to be twisted. Scientists believe it looks this way because the original material in the rings was in clumps that formed streaks as the material orbited Neptune. The motion of the spacecraft added to the twisted appearance by causing a slight smearing in the image. *(Courtesy NASA/JPL)*

Rings of Neptune

The following table is a summary of the rings of Neptune.

Name	Distance*	Width	Thickness	Mass	Albedo
1989N3R	41,900 km	15 km	?	?	low
1989N2R	53,200 km	15 km	?	?	low
1989N4R	53,200 km	5,800 km	?	?	low
1989N1R	62,930 km	< 50 km	?	?	low

*The distance is measured from the planet center to the start of the ring.

Neptune Moon Summary

The following table summarizes the radius, mass and distance from the planet center of each of the moons of Neptune:

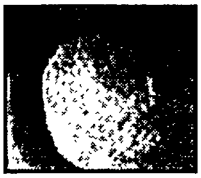
Moon	Radius	Mass	Distance
Naiad (1989N6)	25 km	?	48,000 km
Thalassa (1989N5)	40 km	?	50,000 km
Despina (1989N3)	90 km	?	52,500 km
Galatea (1989N4)	75 km	?	62,000 km
Larissa (1989N2)	95 km	?	73,600 km
Proteus (1989N1)	200 km	?	117,600 km
Triton	1,350 km	2.14x10^22 kg	354,800 km
Nereid	170 km	?	5,513,400 km

Solar System Home

Voyage to Pluto

Other Moons of Neptune

These are some of the other moons of Neptune.



Proteus (1989N1)

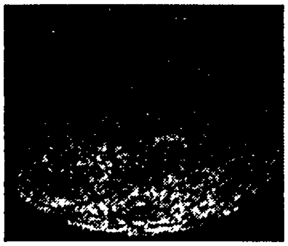
Proteus Statistics

- Radius: 200 km
- Mass: ?
- Density: ?
- Distance from Neptune: 117,600 km
- Orbital period: 1.121 days
- Orbital inclination: 0°
- Orbital eccentricity: 0
- Magnitude (Vo): 20

Larissa (1989N2)

Larissa Statistics

- Radius: 95 km
- Mass: ?
- Density: ?
- Distance from Neptune: 73,600 km
- Orbital period: 0.554 days
- Orbital inclination: 0°
- Orbital eccentricity: 0
- Magnitude (Vo): 21



Triton

Triton is the largest moon of Neptune with a diameter of 2,700 km (1,680 miles). It is colder than any other measured object in the Solar System with a surface temperature of 38° Kelvin (–391° F). It has an extremely thin atmosphere. Nitrogen ice particles may form thin clouds a few kilometers above the surface.

Triton is scarred by enormous cracks. Voyager 2 images showed active geyser like eruptions spewing nitrogen gas and dark dust particles into the atmosphere.

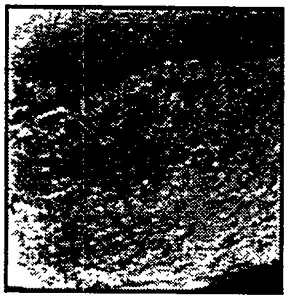
Some scientists suggest that Triton may have once been a planet on its own circling the Sun, and that it was captured by interaction with the combined gravitational influences of the Sun and Neptune to become a moon.

Triton Statistics

- Radius: 1,350 km
- Mass: 2.14x10^22 kg
- Density: 2.07 g/cm^3
- Distance from Neptune: 354,800 km
- Orbital period: 5.877 days
- Orbital inclination: 157°
- Orbital eccentricity: 0
- Magnitude (Vo): 13.6

Views of Triton

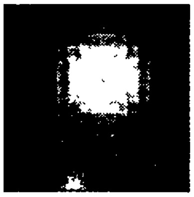
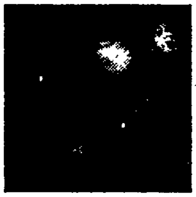
Triton: Voyager 2 obtained this color image of Neptune's large satellite Triton during its close flyby on Aug. 25, 1989. The large south polar cap at the bottom of the image is highly reflective and slightly pink in color; it may consist of a slowly evaporating layer of nitrogen ice deposited during the previous winter. From the ragged edge of the polar cap northward the satellite's face is generally darker and redder in color. This coloring may be produced by the action of ultraviolet light and magnetospheric radiation upon methane in the atmosphere and surface. Running across this darker region, approximately parallel to the edge of the polar cap, is a band of brighter white material that is almost bluish in color. The underlying topography in this bright band is similar; however, to that in the darker redder regions surrounding it.



South Pole: This high resolution image of Triton was obtained by Voyager 2 on August 25, 1989. It show's the moons south polar cap. One of the unusual aspect of this image is the dark streaks in the images. Perhaps they were made by geyser–like eruptions of nitrogen. The geyser eruptions could have carried darker materials from the crust. The light regions probably consist of layers of nitrogen.

Plain of Ice: This view of Triton shows a plain of ice. It was probably formed by eruptions of water or a water–ammonia slurry. It seems to fill the remains of an ancient impact basin.

Solar System Home



Pluto

<u>Chronology of Pluto Exploration</u>

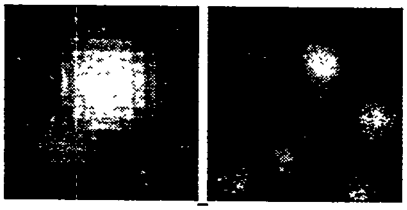
On February 18, 1930, Pluto, the last planet and the 9th in our solar system, was discovered. Normally Pluto is farther from the sun then any other planet; however, due to the <u>eccentricity</u> of its orbit, 20 years out of its 249 orbital years it is closer than <u>Neptune</u>. Pluto's orbit is also highly inclined — tilted 17 degrees to the orbital plane of the other planets. Ground–based observations indicate that Pluto's surface is covered with methane ice and that there is a thin atmosphere that may freeze and fall to the surface as the planet moves away from the Sun. Observations also show that Pluto's spin axis is tipped by 122 degrees.

Pluto has one satellite named Charon, after the boatman in Greek mythology who operated the ferry across the River Styx to Pluto's relm in the underworld. Charon was discovered in 1978. Its surface composition seems to be different from Pluto's. The moon appears to be covered with water–ice rather than methane ice. Its orbit is gravitationally locked with Pluto, so both bodies always keep the same <u>hemisphere</u> facing each other. Pluto's and Charon's rotational period and Charon's orbital period are all 6.3872 Earth days.

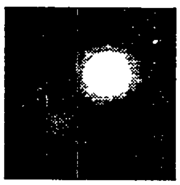
Pluto Statistics

- Mean distance from the Sun: 39.5294 AU (5.91352 x 10^9 km)
- Equatorial radius: 1,160 km
- Mass: 1.29 x 10^22 kg
- Mean density: 2.03 gm/cm^3
- Rotational Period: 6.3872 days
- Orbital period: 248.54 years
- Mean orbital velocity: 4.74 km/s
- Equatorial surface gravity: 0.4 m/s^2
- Equatorial escape velocity: 1.1 km/s
- Orbital eccentricity: 0.2482
- Obliquity: 122.5°
- Orbit Inclination: 17.15°
- Visual Geometric Albedo: 0.5

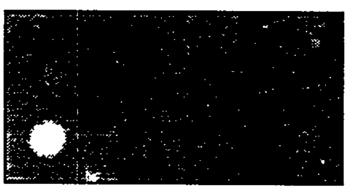
Views of Pluto & Charon



Pluto and Charon: The first image shows a ground based view of Pluto and Charon. The second image shows a Hubble telescope view.



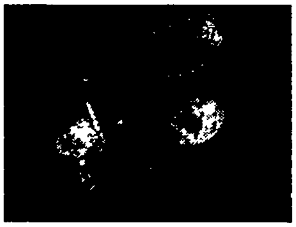
Nordic Optical Telescope: This image of Pluto was taken with the 2.6 m Nordic Optical Telescope, located at La Palma, Canary Islands. It is a good example of the best imagery that can be obtained from earth based telescopes. (c) Nordic Optical Telescope Scientific Association (NOTSA).



New Hubble Telescope Image: This is the clearest view yet of the distant planet Pluto and its moon, Charon, as revealed by the Hubble Space Telescope (HST). The image was taken on February 21, 1994, when the planet was 4,400 million kilometres from the Earth.

The HST corrected optics show the two objects as clearly separate and sharp disks. This now allows astronomers to measure directly (to within about 1 percent) Pluto's diameter of 2320 kilometres and Charon's diameter of 1270 kilometres.

The HST observations show that Charon is bluer than Pluto. This means that the worlds have different surface composition and structure. A bright highlight on Pluto indicates that it may have a smoothly reflecting surface layer. A detailed analysis of the HST image also suggests that there is a bright area parallel to the equator of Pluto. However, subsequent observations are needed to confirm is this feature is real. The new HST image was taken when Charon was near its maximum elongation from Pluto (0.9 arcseconds). The two worlds are 19,640 kilometres apart. *(Courtesy NASA/ESA/ESO).*



Pluto Flyby: This computer graphics frame simulates the Pluto Fast Flyby spacecraft's encounter of the solar system's most distant planet. Pluto is the lower body, whereas its moon, Charon, is the closer body at top. Attached to the spacecraft's hexagonal composite structure are spherical propulsion tanks and, at bottom, a radioisotope thermoelectric generator (RTG) to provide power at the great distance from the sun. At the very end of the RTG assembly is a set of attitude–control thrusters. The dish at upper right is the spacecraft's high–gain antenna used for contact with Earth. Science instruments are located inside the spacecraft bus; on the left hand side of the bus are louvers used to vent heat and maintain the bus's internal temperature. This rendering shows the spacecraft's 1993 configuration; the surfaces of Pluto and Charon shown are speculative. Under development at the Jet Propulsion Laboratory for a launch in 2000 or 2001, the spacecraft would pass within about 15,000 kilometers (9,300 miles) of Pluto and Charon between the years 2007 and 2010. *(Courtesy NASA/JPL).*

Pluto Moon Summary

The following table summarizes the radius, mass and distance from the center of Pluto to Charon:

Moon	Radius	Mass	Distance
Charon	635 km	1.77x10^21 kg	19,640 km

Visit the Asteroids

Asteroids

Chronology of Asteroid Exploration

Asteroids are rocky and metallic objects that orbit the Sun but are too small to be considered planets. They are known as *minor planets*. They have been found inside Earth's orbit to beyond Saturn's orbit. Most, however, are contained within a *main belt* that exists between the orbits of Mars and Jupiter. Some have orbits that cross Earth's path, and some have even hit the Earth in times past. One of the best preserved examples is *Meteor Crater* near Winslow, Arizona.

Asteroids are material left over from the formation of the solar system. One theory suggests that they are the remains of a planet that was destroyed in a massive collision long ago. More likely, asteroids are material that never coalesced into a planet. In fact, if the estimated total mass of all asteroids was gathered into a single object, the object would be less than 1,500 kilometers (932 miles) across — less than half the diameter of our Moon.

Much of our understanding about asteroids comes from examining pieces of space debris that fall to the surface of Earth. Asteroids that are on a collision course with Earth are called meteoroids. When a meteoroid strikes our atmosphere at high velocity, friction causes this chunk of space matter to incinerate in a streak of light known as a meteor. If the meteoroid does not burn up completely, what's left strikes Earth's surface and is called a meteorite.

Of all the meteorites examined, 92.8 percent are composed of silicate (stone), and 5.7 percent are composed of iron and nickel; the rest are a mixture of the three materials. Stony meteorites are the hardest to identify since they look very much like terrestrial rocks.

Since asteroids are material from the very early solar system, scientists are interested in their composition. Spacecraft that have flown through the asteroid belt have found that the belt is really quite empty and that asteroids are separated by very large distances. Recently the Galileo spacecraft has made close encounters with the asteroids 951 Gaspra and 243 Ida. *(Courtesy NASA/JPL).*

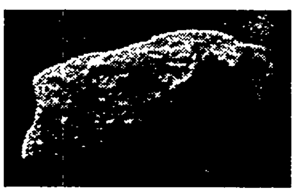
The following images show some of the asteroids that have been studied:

 **Gaspra**

The Galileo spacecraft passed by asteroid 951 Gaspra on October 29, 1991. Gaspra is roughly 17 km (10 mi) long, 10 km (6 mi) wide. Several craters are visible on Gaspra, but none approach the scale of the asteroid's radius. The fact that Gaspra lacks any large craters attests to Gaspra's comparatively recent origin from the collisional breakup of a larger body. The Sun is shining from the right; phase angle is 50 degrees. *(Courtesy NASA/JPL).*

Additional Images of Gaspra

- Eleven Views of Gaspra
- Gaspra Compared to Deimos and Phobos

 **Ida**

This view of the asteroid 243 Ida was acquired by the Galileo spacecraft's solid state imaging system at ranges of 3,057 to 3,821 kilometers (1,900 to 2,375 miles) on August 28, 1993, about 3 1/2 minutes before the spacecraft made its close approach to the asteroid. Galileo flew about 2,400 kilometers (1,500 miles) from Ida at a relative velocity of 12.4 km/sec (28,000 mph). Asteroid and spacecraft were 441 million kilometers (274 million miles) from the Sun.

Ida is the second asteroid ever encountered by a spacecraft. It appears to be about 52 kilometers (32 miles) in length, 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 precursor asteroid in a catastrophic collision.

This view shows numerous craters, including many degraded craters larger than any seen on Gaspra. The south pole is believed to be in the dark side near the middle of the asteroid. *(Courtesy NASA/JPL).*

Ida and Moon

This image is the first full picture showing both asteroid 243 Ida and its newly discovered moon transmitted to Earth from NASA's Galileo spacecraft — the first conclusive evidence that natural satellites of asteroids exist. Ida is the large object to the left, about 56 kilometers (35 miles) long. Ida's natural satellite is the small object to the right. This portrait was taken by Galileo's camera on August 28, 1993, about 14 minutes before the spacecraft's closest approach to the asteroid, from a range of 10,870 kilometers (6,755 miles).

Ida is a heavily cratered, irregularly shaped asteroid in the main asteroid belt between Mars and Jupiter — the 243rd asteroid to be discovered since the first one was found at the beginning of the 19th century. It is a member of a group of asteroids called the Koronis family. The small satellite, which is about 1.5 kilometers (1 mile) across in this view, has yet to be given a name by astronomers. It has been provisionally designated "1993 (243) 1" by the International Astronomical Union. Although the satellite appears to be "next" to Ida it is actually slightly in the foreground, closer to the spacecraft than Ida. Combining this image with data from Galileo's near infrared mapping spectrometer, the science team estimates that the object is about 100 kilometers (60 miles) away from the center of Ida. *(Courtesy NASA/JPL).*

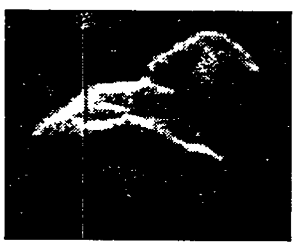
Ida's Moon

This image is the most detailed picture of the recently discovered natural satellite of asteroid 243 Ida taken by the Galileo spacecraft's solid–state imaging camera during its encounter with the asteroid on August 28, 1993. 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 at a range of about 3,900 kilometers (2,400 miles), just over 4 minutes before the spacecraft's closest approach to Ida. Each picture element spans about 39 meters (125 feet) on the surface of the moon.

More than a dozen craters larger than 80 meters (250 feet) in diameter are clearly evident, indicating that the moon has suffered numerous collisions from smaller solar system debris during its history. The larger crater on the terminator is about 300 meters (1,000 feet) across. The satellite is approximately egg–shaped, measuring about 1.2 by 1.4 by 1.6 kilometers (0.75 by 0.87 by 1 mile). 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. This image was relayed to Earth from Galileo on June 8, 1994. *(Courtesy NASA/JPL).*

Additional Images of Ida

- Six Views of Ida
- High Resolution Image of Ida's Limb
- Color Picture of Ida and its moon
- First Image of Ida's Moon
- Early Image of Ida's Moon



Toutatis

These are radar images of asteroid 4179 Toutatis made during the object's recent close approach to Earth. The images reveal two irregularly shaped, cratered objects about 4 and 2.5 kilometers (2.5 and 1.6 miles) in average diameter which are probably in contact with each other. The four frames shown in the full picture (from upper left to upper right, lower left to lower right) were obtained on Dec. 8, 9, 10 and 13 when Toutatis was an average of about 4 million kilometers (2.5 million miles) from Earth. On each day, the asteroid was in a different orientation with respect to Earth. In these images, the radar illumination comes from the top of the page, so parts of each component facing toward the bottom are not seen. The large crater shown in the Dec. 9 image (upper right) is about 700 meters (2,300 feet) in diameter. *(Courtesy NASA/JPL).*

Castalia

This full picture shows 16 different views of a 3D computer model of the near Earth asteroid 4769 Castalia. The model was created by using radar data obtained by Ostro and others in 1989 when the asteroid passed within 5.6 million kilometers (3.5 million miles) of Earth, using the Arecibo radar/radio telescope in Puerto Rico. The double lobed object is about 1.8 kilometers (a little over a mile) across at its widest. The effective resolution of the reconstruction is about 100 meters (330 feet). This is the first detailed 3D model of a near Earth asteroid yet produced, and the most conclusive evidence to date of a "contact–binary" object in the solar system. *(Courtesy NASA/JPL).*

Solar System Home

Visit the Comets

Comets

A detailed tutorial on comets with a focus on the Shoemaker–Levy Comet impact event is HERE.

News Flash! Look for images of the Comet Shoemaker/Levy impact on Jupiter HERE.

- Shoemaker–Levy 9/Jupiter Collision Information & Images
- Comet Shoemaker–Levy 9 Impact from JPL

Chronology of Comet Space Exploration

Comets are small, fragile, irregularly shaped bodies composed of a mixture of non–volatile grains and frozen gases. They usually follow highly elongated paths around the Sun. Most become visible, even in telescopes, only when they get near enough to the Sun for the Sun's radiation to start subliming the volatile gases, which in turn blow away small bits of the solid material. These materials expand into an enormous escaping atmosphere called the coma, which becomes far bigger than a planet, and they are forced back into long tails of dust and gas by radiation and charged particles flowing from the Sun. Comets are cold bodies, and we see them only because the gases in their comae and tails fluoresce in sunlight (somewhat akin to a fluorescent light) and because of sunlight reflected from the solids. Comets are regular members of the solar system family, gravitationally bound to the Sun. They are generally believed to be made of material, originally in the outer part of the solar system, that didn't get incorporated into the planets. It is the very fact that they are thought to be composed of such unchanged primitive material that makes them extremely interesting to scientists who wish to learn about conditions during the earliest period of the solar system.

The nucleus of a comet, which is its solid, persisting part, has been called an icy conglomerate, a dirty snowball, and other colorful but even less accurate descriptions. Certainly a comet nucleus contains silicates akin to some ordinary Earth rocks in composition, probably mostly in very small grains and pieces. Perhaps the grains are glued together into larger pieces by the frozen gases. A nucleus appears to include complex carbon compounds and perhaps some free carbon, which make it very black in color. Most notably, at least when young, it contains many frozen gases, the most common being ordinary water. In the low pressure conditions of space, water sublimes, that is, it goes directly from solid to gas. Water probably makes up 75–80% of the volatile material in most comets.

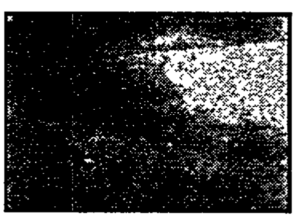
Other common ices are carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), ammonia (NH_3), and formaldehyde (H_2CO). Volatiles and solids appear to be fairly well mixed throughout the nucleus of a new comet approaching the Sun for the first time. As a comet ages from many trips close to the Sun, there is evidence that it loses most of its ices, or at least those ices anywhere near the nucleus surface, and becomes just a very fragile old rock in appearance, indistinguishable at a distance from an asteroid. *(Courtesy NASA/JPL).*

Shoemaker/Levy Comet

Shoemaker/Levy This view shows the Comet P/Shoemaker–Levy 9 obtained by the Hubble Space Telescope in 1993. P/Shoemaker–Levy 9 is a comet which was broken up under the influence of Jupiter's gravity. It will plunge into Jupiter's atmosphere in July 1994.

The Students for the Exploration and Development of Space are maintaining a page about the comet impact event on Jupiters.

Halley's Comet

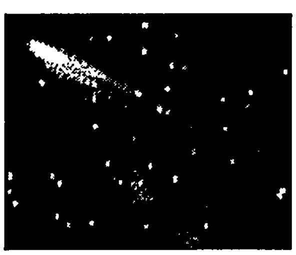


Ion Tail The well developed tail structure of Comet Halley was captured in this image taken March 5, 1986. At this point in its orbit, Halley had recently passed perihelion on February 9, 1986 and was at its most active. This 10 minute exposure was recorded at Mauna Kea Observatory on IIIa–J emulsion without filters. This image shows both the ion and dust tail, with the latter stretching for over 6 degrees on the sky. *(Courtesy NASA/JPL).*

Detachment Event One of the more spectacular changes recorded for Halley during an apparition was the detachment event that happened April 12, 1986. This 3 minute exposure was taken using the Michigan Schmidt telescope at Cerro Tololo Interamerican Observatory. The resulting image clearly shows part of the ion tail structure detached from the comet. At this period, the orientation of the comet is such that the tail is foreshortened, with the prolonged radius vector pointing west of north. *(Courtesy NASA/JPL).*

Ray Structure An example of the ray structure of Halley was captured on March 19, 1986, at the Mount Wilson/Las Campanas Observatories. This 10 minute exposure was recorded at the focus of the 100 inch telescope on Las Camapanas in Chile. The close up image, covering the inner 1 degree of the comet, shows a prolonged radius vector extending to the left. *(Courtesy NASA/JPL).*

Kohoutek Comet



Comet Kohoutek This color photograph of the comet Kohoutek was taken by members of the lunar and planetary laboratory photographic team from the University of Arizona, at the Catalina observatory with a 35mm camera on January 11, 1974. *(Courtesy NASA).*

Solar System Home

The Spacecraft that made it Possible

History of Space Exploration

Space History

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Introduction

From our small world we have gazed upon the cosmic ocean for untold thousands of years. Ancient astronomers observed points of light that appeared to move among the stars. They called these objects planets, meaning wanderers, and named them after Roman deities — Jupiter, king of the gods; Mars, the god of war; Mercury, messenger of the gods; Venus, the god of love and beauty, and Saturn, father of Jupiter and god of agriculture. The stargazers also observed comets with sparkling tails, and meteors or shooting stars apparently falling from the sky.

Science flourished during the European Renaissance. Fundamental physical laws governing planetary motion were discovered, and the orbits of the planets around the Sun were calculated. In the 17th century, astronomers pointed a new device called the telescope at the heavens and made startling discoveries.

But the years since 1959 have amounted to a golden age of solar system exploration. Advancements in rocketry after World War II enabled our machines to break the grip of Earth's gravity and travel to the Moon and to other planets.

The United States has sent automated spacecraft, then human–crewed expeditions, to explore the Moon. Our automated machines have orbited and landed on Venus and Mars; explored the Sun's environment; observed comets and asteroids, and made close–range surveys while flying past Mercury, Jupiter, Saturn, Uranus and Neptune.

These travelers brought a quantum leap in our knowledge and understanding of the solar system. Through the electronic sight and other "senses" of our automated spacecraft, color and complexion have been given to worlds that for centuries appeared to Earth–bound eyes as fuzzy disks or indistinct points of light. And dozens of previously unknown objects have been discovered.

Future historians will likely view these pioneering flights through the solar system as some of the most remarkable achievements of the 20th century.

(Courtesy NASA/JPL).

Space History Rocket History

A Brief History of Rocketry

The earliest solid rocket fuel was a form of gunpowder, and the earliest recorded mention of gunpowder comes from China late in the third century before Christ. Bamboo tubes filled with saltpeter, sulphur and charcoal were tossed into ceremonial fires during religious festivals in hopes the noise of the explosion would frighten evil spirits.

It's probable that more than a few of these bamboo tubes were imperfectly sealed and, instead of bursting with an explosion, simply went skittering out of the fire, propelled by the rapidly burning gunpowder. Some clever observer whose name is lost to history may have then begun experiments to deliberately produce the same effect as the bamboo tubes which leaked fire.

Certainly by the year 1045 A.D. — 21 years before William the Conqueror would land on the shores of England — the use of gunpowder and rockets formed an integral aspect of Chinese military tactics.

A point of confusion arises tracing the history of rocketry back before 1045. Chinese documents record the use of "fire arrows," a term which can mean either rockets or an arrow carrying a flammable substance.

By the beginning of the 13th Century, the Chinese Sung Dynasty, under pressure from growing Mongolian hordes, found itself forced to rely more and more on technology to counter the threat. Chinese ordnance experts introduced and perfected many types of projectiles, including explosive grenades and cannon.

Rocket fire–arrows were certainly used to repel Mongol invaders at the battle of Kai–fung–fu in 1232 A.D.

The rockets were huge and apparently quite powerful. According to a report: "When the rocket was lit, it made a noise that resembled thunder that could be heard for five leagues — about 15 miles. When it fell to Earth, the point of impact was devastated for 2,000 feet in all directions." Apparently these large military rockets carried incendiary material and iron shrapnel. These rockets may have included the first combustion chamber, for sources describe the design as incorporating an "iron pot" to contain and direct the thrust of the gunpowder propellant.

The rocket seems to have arrived in Europe around 1241 A.D. Contemporary accounts describe rocket–like weapons being used by the Mongols against Magyar forces at the battle of Sejo which preceded their capture of Buda (now known as Budapest) Dec. 25, 1241.

Accounts also describe Mongol's use of a noxious smoke screen –– possibly the first instance of chemical warfare.

Rockets appear in Arab literature in 1258 A.D., describing Mongol invaders' use of them on February 15 to capture the city of Baghdad.

Quick to learn, the Arabs adopted the rocket into their own arms inventory and, during the Seventh Crusade, used them against the French Army of King Louis IX in 1268.

It is certain that, not later than the year 1300, rockets had found their way into European arsenals, reaching Italy by the year 1500, Germany shortly afterwards, and later, England. A 1647 study of the "Art of Gunnery" published in London contains a 43–page segment on rockets. The Italians are credited, by the way, with adopting military rockets for use as fireworks –– completing the circle, so to speak, of the bursting bamboo used at the Chinese festivals 1,700 years earlier.

The French Army traditionally has been among the largest, if not THE largest, army in Europe and was quick to adopt rockets to military operations. Records from 1429 show rockets in use at the siege of Orleans during the Hundred Years War against the English.

Dutch military rockets appear by 1650 and the Germans' first military rocket experiments began in 1668. By 1730, a German field artillery colonel, Christoph Fredrich von Geissler, was manufacturing rockets weighing 55 to 120 pounds.

As the 18th Century dawned, European military experts began to take a serious interest in rockets –– if only because they, like the Magyars 500 years earlier, found themselves on the receiving end of rocket warfare.

Both the French and the British, during the Eighteenth Century, began wrestling for control of the riches of India. In addition to fighting one another, they also found themselves frequently engaged against the Mogol forces of Tippoo Sultan of Mysore. During the two battles of Seringapatam in 1792 and 1799, rockets were used against the British. One of Tippoo Sultan's rockets is now displayed in the Royal Ordnance Museum at Woolwich Arsenal, near London.

Tippoo Sultan's father, Hyder Ally, had incorporated a 1,200 man contingent of rocketeers into his army in the year 1788. Tippoo Sultan increased this force to about 5,000 men, about a seventh of his total Army's strength.

Profiting from their Indian experience, the British, led by Sir William Congrieve

(KON–greeve), began development of a series of barrage rockets ranging in weight from 300 to 18 pounds. Congrieve–design rockets were used against Napoleon.

It is surprising that Napoleon seems to have made no use of rockets in the French Army but it must be remembered Napoleon was an artillery officer and may have simply been too hide–bound a traditionalist to favor new–fangled rockets over more familiar cannons.

The scope of the British use of the Congrieve rocket can be ascertained from the the 1807 attack on Copenhagen. The Danes were subjected to a barrage of 25,000 rockets which burnt many houses and warehouses.

An official rocket brigade was created in the British Army in 1818.

Rockets came to the New World during the War of 1812.

During the Battle of Bladensburg, August 24, 1814, the British 85th Light Infantry used rockets against an American rifle battalion commanded by U.S. Attorney General William Pickney. British Lieutenant George R. Gleig witnessed the Americans' response to the new threat –– "Never did men with arms in their hands make better use of their legs," he wrote.

On December 4, 1846, a brigade of rocketeers was authorized to accompany Maj. Gen. Winfield Scott's expedition against Mexico. The Army's first battalion of rocketeers –– consisting of about 150 men and armed with about 50 rockets –– was placed under the command of First Lieutenant George H. Talcott.

The rocket battery was used March 24, 1847 against Mexican forces at the siege of Veracruz.

On April 8 the rocketeers moved inland, being placed in their firing position by Captain Robert E. Lee (later to command the Confederate Army of Northern Virginia in the War Between the States). About 30 rockets were fired during the battle for Telegraph Hill. Later, the rockets were used in the capture of the fortress of Chapultepec, which forced the surrender of Mexico City.

With typical foresight, as soon as the fighting in Mexico was over, the rocketeer battalion was disbanded and the remaining rockets were placed in storage.

They remained in mothballs for about 13 years –– until 1861 when they were hauled out for use in the Civil War. The rockets were found to have deteriorated, however, so new ones were made.

The first recorded use of rockets in the Civil War came on July 3, 1862, when Maj.

Gen. J.E.B. Stuart's Confederate cavalry fired rockets at Maj. Gen. George B. McClellan's Union troops at Harrison's Landing, Va. No record exists of the Northerners' opinion of this premature "Fourth of July" fireworks demonstration.

Later in 1862, an attempt was made by the Union Army's New York Rocket Battalion — 160 men under the command of British–born Major Thomas W. Lion — to use rockets against Confederates defending Richmond and Yorktown, Virginia. It wasn't an overwhelming success. When ignited, the rockets skittered wildly across the ground, passing between the legs of a number of mules. One detonated harmlessly under a mule, lifting the animal several feet off the ground and precipitating its immediate desertion to the Confederate Army.

The only other documented use of rockets is at Charleston, S.C., in 1864. Union troops under Maj. Gen. Alexander Schimmelfennig found rockets "especially practical in driving off Confederate picket boats, especially at night."

As an interesting sidelight, the author Burke Davis, in his book "Our Incredible Civil War," tells a tale of a Confederate attempt to fire a ballistic missile at Washington, D.C., from a point outside Richmond, Va.

According to the author, Jefferson Davis witnessed the event at which a 12–foot–long, solid–fueled rocket, carrying a 10–pound gunpowder warhead in a brass case engraved with the letters C.S.A., was ignited and seen to roar rapidly up and out of sight. No one ever saw the rocket land. It's interesting to speculate whether, almost 100 years before Sputnik, a satellite marked with the initials of the Confederate States of America might have been launched into orbit.

The military appears to have remained underwhelmed with the potential of rockets. They were employed in fits and starts in many of the brushfire wars which punctuated the otherwise calm closing days of the late Victorian Era. If the military was luke warm to rockets, another profession welcomed them with open arms.

The international whaling industry developed rocket–powered, explosive–tipped harpoons which were most effective against the ocean–going leviathans.

During the First World War, rockets were first fired from aircraft attempting to shoot down enemy hydrogen gas–filled observation balloons. Successes were rare and pilots resisted being asked to fire rockets from the highly flammable, cloth and varnish covered wings of their biplanes. The French were the principal users of aerial rockets, using a model developed by a Naval lieutenant, Y.P.G. LePrieur.

The principal drawback to rockets throughout this period of development was the type of fuel. Both here and abroad, experiments were under way to develop a more powerful, liquid–propelled rocket. Two young men stand out in this effort — one an American, Robert H. Goddard — the other a German, Wernher von Braun.

Radio commentator Paul Harvey tells a story of how young von Braun's interest in rocketry almost got him labeled as a juvenile delinquent. At the age of 13, von Braun exhibited an interest in explosives and fireworks. His father could not understand his son's consuming interest in so dangerous a hobby. He feared his son would become safecracker. One day the young teenager obtained six skyrockets, strapped them to a toy red wagon and set them off. Streaming flames and a long trail of smoke, the wagon roared five blocks into the center of the von Braun family's home town, where they finally exploded.

As the smoke cleared, the toy wagon emerged as a charred wreck. Young von Braun emerged in the firm grasp of a policeman. Despite being severely reprimanded by his father, the youngster's interest would not be denied. By the age of 22 he had earned his doctorate in physics. Two years later he was directing Germany's military rocket development program.

Von Braun and his colleagues produced a number of experimental designs, the most famous of which was the A–4 rocket, which has gained distinction in history under another name — the vengeance weapon number two — V–2 for short. The V–2 was the first successful, long range ballistic missile, and von Braun is credited as its principal developer.

As World War II drew to a close, von Braun led his contingent of several hundred rocket scientists and engineers — all marked for death by the Nazis to prevent their capture by the Allies — into American lines.

In 1946, von Braun and his team arrived at White Sands, N.M., where, for the first time, von Braun learned of work done by the American rocket pioneer Robert Goddard.

Goddard's interest in rockets began in 1898 when, as a 16–year–old, he read the latest publication of that early science fiction writer, English novelist H.G. Wells. The book which so excited Goddard was later made into a 1938 radio program that nearly panicked our entire nation when it was broadcast. Orson Well's too realistic rendition of the "War of the Worlds" still causes many to shudder.

As the 20th Century began — Wilbur and Orville Wright were preparing to become the first men to fly. Goddard, however, was already designing rockets to probe the upper atmosphere and delve into space. Half a world away — and unknown to Goddard — a Russian school teacher, Konstantin Tsiolkovsky was thinking along much the same lines. Both came to the conclusion independently that, if a rocket was going to do the things they dreamed of, it would have to be powered by liquid fuels. Solid fuels of the time simply didn't have sufficient power. Tsiolkovski lacked Goddard's practicality. While Tsiolkovski worked out many principles of astronautics and designed suitable rockets, he never built any. By contrast, Goddard was a technical man. He could and did build rockets. By the time he died in 1945, Goddard held 214 patents in rocketry — patents which still produce royalties for his estate.

Goddard began his experiments in rocketry while studying for his doctorate at Clark University in Worcester, Mass.

He first attracted attention in 1919 when he published a paper titled, "A Method of Reaching Extreme Altitudes." In his paper he outlined his ideas on rocketry and suggested, none too seriously, that a demonstration rocket should be flown to the Moon.

The general public ignored the scientific merit of the paper — latching instead onto Goddard's Moon rocket proposal. At the time, such an endeavor was absurd and most dismissed Goddard as a "crank."

The experience taught Goddard a hard lesson — one which caused him to shy away from future opportunities to publicize his work. Publicity was far from Goddard's mind on the morning of March 16, 1926. On that day, barely a year after Wernher von Braun's rocket wagon fiasco, Goddard launched a liquid–powered rocket he had designed and built from a snow–covered field at his Aunt Effie Goddard's farm in Auburn, Mass. The rocket flew — 152 feet — about the same distance as the Wright Brothers' first manned flight — but it did fly! It was the first flight of a liquid–fueled rocket in history.

When Goddard was later approached by the American Interplanetary Society in 1930 to publicize his work, Goddard refused. The society, rebuffed and learning that no one in the United States aside from Goddard was working with rockets, turned its attention to rocket research under way in Europe, where rocketry was beginning to develop a following.

In the spring of 1931, two founder–members of the American society, husband and wife Edward and Lee Pendray, travelled on vacation to Germany where they made contact with the German Rocket Society, which had been formed in 1927. The visiting Americans were given a preview of the future when a member of the German Rocket Society — Prof. Willy Ley — took the pair to the Germans' rocket flying test ground in the suburbs of Berlin.

Returning home, the Pendrays filed an enthusiastic report of their visit, prompting the American society to build its first rocket. The attempted test flight in November 1932 ended with the American design firmly on the ground. It's unfortunate the Pendrays didn't meet another future rocketry hall–of–famer who also was a member of the German society. Rumanian–born Hermann Oberth wrote, in 1923, a highly prophetic book: "The Rocket into Interplanetary Space." The book enthralled many with dreams of space flight, including that precocious German teenager, Wernher von Braun who read the book in 1925. Five years later, von Braun had joined Oberth and was assisting with rocket experiments.

By 1932, the German Army was beginning to show an interest in the German Rocket Society's efforts, and in July of that year, a "Mirak" rocket was launched as a demonstration for the head of the newly created German Army rocket research group, Captain (later Major General) Walter Dornberger.

Mirak didn't impress Dornberger.

Von Braun did.

Three months after the demonstration flight, von Braun was engaged to work on liquid propelled rockets for the Army. Most of the German Rocket Society followed von Braun into national service and the society disbanded.

By December 1934, von Braun scored his first successes with an A2 rocket powered by ethanol and liquid oxygen. Two years later, as plans for the follow–on A3 rocket were being finalized, initial planning began for the A4 rocket –– a rocket that was to be, in Dornberger's words, a practical weapon, not a research tool. As noted earlier, most know the A4 by another name –– the V–2.

The rocket researchers quickly outgrew their facilities at Kummersdorf on the outskirts of Berlin and, in 1936, operations were transferred to a remote island on Germany's Baltic coast –– Peenemuende.

Between 1937 and 1941, von Braun's group launched some 70 A3 and A5 rockets, each testing components for use in the proposed A4 rocket.

The first A4 rocket flew in March 1942. The rocket barely cleared some low clouds before crashing into the sea a half mile from the launch site.

The second launch in August 1942 saw the A4 rise to an altitude of 7 miles before exploding.

The third try was the charm. On October 3, 1942, another A4 roared aloft from

Peenemuende, followed its programmed trajectory perfectly, and landed on target 120 miles away. This launch can fairly be said to mark the beginning of the space age. The A4, the first successful ballistic rocket, is the ancestor of practically every rocket flown in the world today.

Production of the A4 began in 1943 and the first A4s, now renamed V2s, were launched against London in September 1944.

The V–2 offensive came too late to affect the course of the war. By April 1945, the German Army was in full retreat everywhere and Hitler had committed suicide in his bunker in Berlin.

At an inn near Oberjoch, the Haus Ingeburg, von Braun and over 100 of his rocket experts waited for the end. The entire team had been ordered executed by Hitler to prevent their capture. Wernher von Braun's brother, Magnus, however, managed to contact nearby American forces before Hitler's SS henchmen could reach the rocket team. On May 2, the same day Berlin fell to the Soviet Army, von Braun and his rocket team entered American lines and safety.

With the fighting over, von Braun and his team were heavily interrogated and jealously protected from Russian agents. V2s and V2 components were assembled. German rocket technicians were rounded up. In June, General Eisenhower sanctioned the final series of V2 launches in Europe. Watching each of the three V2s which rose from a launch site at Cuxhaven was a Russian Army colonel, Sergei Korolev. Ten years later, Korolev would be hailed as the Soviet Union's chief designer of spacecraft and the individual responsible for building the Vostok, Voshkod and Soyuz spacecraft which, since 1961, have carried all Soviet cosmonauts into orbit.

Few members of von Braun's team participated in the Cuxhaven launches. Most had already begun setting up shop at Fort Bliss, near El Paso, Texas. Piled up in the desert near Las Cruces, New Mexico, were enough parts to build 100 V2s. Von Braun and his team soon moved to nearby White Sands Proving Ground where work began assembling and launching V2s. By February 1946, von Braun's entire Peenemuende team had been reunited at White Sands and, on April 16, the first V2 was launched in the United States. The U.S. space program was under way!

Up to 1952, 64 V2s were launched at White Sands. Instruments, not explosives, packed the missiles' nosecones. A V2 variant saw the missile become the first stage of a two stage rocket named Bumper. The top half was a WAC Corporal rocket. The need for more room to fire the rockets quickly became evident and, in 1949, the Joint Long Range Proving Ground was established at remote, deserted Cape Canaveral, Fla. On July 24, 1950, a two–stage Bumper rocket became the first of hundreds to be launched from "the Cape."

The transfer of launch operations to the Cape coincided with the transfer of the Army's missile program from White Sands to a post just outside a north Alabama cotton town called Huntsville. Von Braun and his team arrived in April 1950 –– it was to remain his home for the next 20 years –– 20 years in which the city's population increased ten fold.

The Von Braun team worked to develop what was essentially a super–V2 rocket, named for the U.S. Army arsenal where it was being designed –– the Redstone.

In 1956, the Army Ballistic Missile Agency was established at Redstone Arsenal under von Braun's leadership to develop the Jupiter intermediate range ballistic missile. A version of the Redstone rocket, known as the Jupiter C, on January 31, 1958, was used to launch America's first satellite, Explorer I. Three years later, Mercury Redstones launched Alan Sheppard and Gus Grissom on suborbital space flights, paving the way for John Glenn's first orbital flight.

In 1958, NASA was established, and, two years later, von Braun, his team, and the entire Army Ballistic Missile Agency were transferred to NASA to become the nucleus of the agency's space program.

The Army Missile Command, which owns Redstone Arsenal, continued its vital national defense mission after the transfer of ABMA to NASA, chalking up a remarkable number of successful programs to augment America's landpower. MICOM's successes include the Pershing II, the NIKE weapons systems, the HAWK system, Improved HAWK, Corporal, Sergeant, Lance and Chaparral, to name a few.

Pursuing a separate course –– that of developing rockets for space exploration –– the Marshall Space Flight Center's past quarter century has been a time of superlatives.

In 1961, almost as Alan Sheppard was drying off from his landing in the Atlantic following his riding a Marshall–designed Redstone rocket on a sub–orbital flight which made him the first American in space, President Kennedy committed this nation to being first on the Moon. NASA's Marshall Center was charged with developing the family of giant rockets which would take us there.

The Saturn rockets developed at Marshall to support the Apollo program and to honor President Kennedy's pledge were, at the time, the most powerful space launch vehicles yet to have been invented.

Engineers, scientists, contractors, and other support personnel built well. On July

20, 1969, a transmission from the Moon's Sea of Tranquility reported "the Eagle has landed."

Marshall's Saturn rockets first took us around the Moon, then to its cratered surface. Marshall–developed lunar excursion vehicles –– the ungainly Moon Buggies –– carried astronauts on far–ranging excursions in pursuit of samples of lunar soil and rock.

Closer to home, the team at Marshall developed America's first space station –– Skylab. Built to replace the upper stage of a Saturn V moon rocket, the Skylab module was successfully placed in orbit early on May 14, 1973.

Placing Skylab in orbit marked a major transition in the story of rocketry. Up until Skylab, the rocket had been the star –– the featured attraction. The focus had been on the up and down –– launch and recovery. Skylab, in essence stole the show. For the first time, space became a place in which to live and work. Flying aboard a rocket was about the Earthside equivalent of driving the family car to work. Just as having to drive to work is only incidental to work itself –– flying aboard a rocket became secondary to the work done once Skylab had been reached. The rocket, simply stated, became a means to an end –– the end in this case being the opportunity to learn to live and work in space.

A rash of malfunctions plagued Skylab's early days –– problems which tested the resourcefulness of the entire NASA team. The problems were overcome, however, and Skylab went on to become one of Marshall's proudest achievements.

A Marshall–developed Saturn I–B also carried aloft America's half of the first –– and only –– joint U.S.–Soviet space endeavor, the Apollo–Soyuz project.

After Apollo, the team at Marshall tackled designing a revolutionary national space transportation system, which came to be known simply as "The Space Shuttle."

It is anything but simple!

The space shuttle main engines are among the most powerful, most sophisticated devices ever invented. They represent a quantum leap in technology advancement over the engines which powered the Saturn V. Each of the three main engines in tail of the shuttle can provide almost a half–million pounds of thrust, a thrust equal to that produced by all eight of the Saturn I's first stage engines. Unlike most previous rocket engines, which were designed to be used only once –– and then for only a few minutes –– the space shuttle's main engines are designed to be used again and again, for up to 7.5 hours. The thrust to weight ratio for these engines is the best in the world — each engine weighs less than 7,000 pounds but puts out the power equivalent of seven Hoover Dams!

Twenty–four successful flights of the space shuttle lulled America into a sense of complacency. Shuttle launches became routine — a ho–hum event which had to scramble for an inch or two on page 2.

Then came the Challenger disaster....

The time since the loss of Challenger has been the busiest in the history of Marshall Space Flight Center. Teams of experts have been organized to find and fix the problems which led to the accident. Investigation quickly focused on a defective joint in the space shuttle's solid rocket motors. Rocket propulsion experts devised a number of modifications to the solid rocket motor design to remedy the fault.

A vigorous test program is now under way to show the problems have been solved.

The disaster–enforced hiatus in shuttle operations has given Marshall — and other NASA installations — an opportunity to address other shuttle–related concerns. Major steps have been made at enhancing the reliability and safety of the turbine blades and turbo pumps in the shuttle's main engines. An escape system has been examined for the shuttle crew. Improvements have been made to the orbiter's landing gear and brakes.

When America returns to manned spaceflight, it will do so in a space vehicle which is vastly safer and more capable.

NASA also is examining using expendable launch vehicles on missions which do not require the shuttle's unique capabilities, and is looking into development of a new generation of heavy lift launch vehicles.

These will become the next chapter in the story of rocketry — a story whose first chapters were written more than 2,400 years ago.

No one can say where our path will lead or when — hopefully never — the last chapter in this history will be written.

(Courtesy KSC/NASA).

Space History Early Astronauts

Early Astronaut Selection and Training

Spacemen of fiction – Jules Verne's travelers to the Moon, or the comic strip heroes Flash Gordon and Buck Rogers – were familiar characters midway through the 20th Century, but nobody could describe accurately a real astronaut. There were none.

Then in 1959 the National Aeronautics and Space Administration asked the United States military services to list their members who met specific qualifications. The search was underway for pilots for the exciting new manned space flight program.

In seeking its first space pilots, NASA emphasized jet aircraft flight experience and engineering training, and it tailored physical stature requirements to the small cabin space available in the Mercury capsule then being designed. Basically, those 1959 requirements were: Less than 40 years of age; less than 5ft. 11 inches tall; excellent physical condition; bachelor's degree or equivalent in engineering; qualified jet pilot; graduate of test pilot school, and at least 1500 hours of flying time.

More than 500 hundred men qualified. Military and medical records were examined; psychological and technical tests were given; personal interviews were conducted by psychological and medical specialists. At the end of the first screening, many candidates were eliminated and others decided they did not want to be considered further.

Even more stringent physical and psychological examinations followed, and in April 1959 NASA announced its selection of seven men as the first American astronauts. They were Navy Lieutenant M. Scott Carpenter; Air Force Captains L. Gordon Cooper, Jr., Virgil I. "Gus" Grissom, and Donald K. "Deke" Slayton; Marine Lieutenant Colonel John H. Glenn, Jr., and Navy Lieutenant Commanders Walter M. Schirra, Jr., and Alan B. Shepard, Jr.

Each flew in Project Mercury except Slayton, who was grounded with a previously undiscovered heart condition. After doctors certified that the condition had cleared up, Slayton realized his ambition to fly in space 16 years after his selection. He was a member of the American crew of the Apollo Soyuz Test Project in July 1975, the world's first international manned space flight.

More Recruiting

Three years after that first selection, NASA issued another call for Gemini and

Apollo astronaut trainees. Experience in flying high–performance aircraft still was stressed, as was education. The limit on age was lowered to 35 years, the maximum height raised to 6 feet, and the program was opened to qualified civilians. This second recruitment brought in more than 200 applications. The list was screened to 32, then finally pared to nine in September 1962.

Fourteen more astronaut trainees were chosen from nearly 300 applicants in October 1963. By then, prime emphasis had shifted away from flight experience toward superior academic qualifications. In October 1964 applications were invited on the basis of educational background alone. These were the scientist–astronauts, so called because the 400–plus applicants who met minimum requirements had a doctorate or equivalent experience in natural sciences, medicine, or engineering.

These applications were turned over to the National Academy of Sciences in Washington for evaluation. Sixteen were recommended to NASA, and six were selected in June 1965. Although the call for volunteers did not specify flight experience, two of the applicants were qualified jet pilots and did not need the year of basic flight training given the others.

Another 19 pilot astronauts were brought into the program in April 1966, and 11 scientist–astronauts were added in mid–1967. When the Air Force Manned Orbiting Laboratory program was cancelled in mid 1969, seven astronaut trainees transferred to NASA.

(Courtesy KSC/NASA).

Space History Automated Spacecraft

Automated Spacecraft

The National Aeronautics and Space Administration's (NASA's) automated spacecraft for solar system exploration come in many shapes and sizes. While they are designed to fulfill separate and specific mission objectives, the craft share much in common.

Each spacecraft consists of various scientific instruments selected for a particular mission, supported by basic subsystems for electrical power, trajectory and orientation control, as well as for processing data and communicating with Earth.

Electrical power is required to operate the spacecraft instruments and systems. NASA uses both solar energy from arrays of photovoltaic cells and small nuclear generators to power its solar system missions. Rechargeable batteries are employed for backup and supplemental power.

Imagine that a spacecraft has successfully journeyed millions of miles through space to fly but one time near a planet, only to have its cameras and other sensing instruments pointed the wrong way as it speeds past the target! To help prevent such a mishap, a subsystem of small thrusters is used to control spacecraft.

The thrusters are linked with devices that maintain a constant gaze at selected stars. Just as Earth's early seafarers used the stars to navigate the oceans, spacecraft use stars to maintain their bearings in space. With the subsystem locked onto fixed points of reference, flight controllers can keep a spacecraft's scientific instruments pointed at the target body and the craft's communications antennas pointed toward Earth. The thrusters can also be used to fine–tune the flight path and speed of the spacecraft to ensure that a target body is encountered at the planned distance and on the proper trajectory.

Between 1959 and 1971, NASA spacecraft were dispatched to study the Moon and the solar environment; they also scanned the inner planets other than Earth –– Mercury, Venus and Mars. These three worlds, and our own, are known as the terrestrial planets because they share a solid–rock composition.

For the early planetary reconnaissance missions, NASA employed a highly successful series of spacecraft called the Mariners. Their flights helped shape the planning of later missions. Between 1962 and 1975, seven Mariner missions conducted the first surveys of our planetary neighbors in space.

All of the Mariners used solar panels as their primary power source. The first and the final versions of the spacecraft had two wings covered with photovoltaic cells. Other Mariners were equipped with four solar panels extending from their octagonal bodies.

Although the Mariners ranged from the Mariner 2 Venus spacecraft, weighing in at 203 kilograms (447 pounds), to the Mariner 9 Mars Orbiter, weighing in at 974 kilograms (2,147 pounds), their basic design remained quite similar throughout the program. The Mariner 5 Venus spacecraft, for example, had originally been a backup for the Mariner 4 Mars flyby. The Mariner 10 spacecraft sent to Venus and Mercury used components left over from the Mariner 9 Mars Orbiter program.

In 1972, NASA launched Pioneer 10, a Jupiter spacecraft. Interest was shifting to four of the outer planets –– Jupiter, Saturn, Uranus and Neptune –– giant balls of dense gas quite different from the terrestrial worlds we had already surveyed.

Four NASA spacecraft in all –– two Pioneers and two Voyagers –– were sent in the 1970s to tour the outer regions of our solar system. Because of the distances involved, these travelers took anywhere from 20 months to 12 years to reach their destinations. Barring faster spacecraft, they will eventually become the first human artifacts to journey to distant stars. Because the Sun's light becomes so faint in the outer solar system, these travelers do not use solar power but instead operate on electricity generated by heat from the decay of radioisotopes.

NASA also developed highly specialized spacecraft to revisit our neighbors Mars and Venus in the middle and late 1970s. Twin Viking Landers were equipped to serve as seismic and weather stations and as biology laboratories. Two advanced orbiters –– descendants of the Mariner craft –– carried the Viking Landers from Earth and then studied martian features from above.

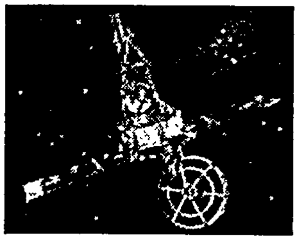
Two drum–shaped Pioneer spacecraft visited Venus in 1978. The Pioneer Venus Orbiter was equipped with a radar instrument that allowed it to "see" through the planet's dense cloud cover to study surface features. The Pioneer Venus Multiprobe carried four probes that were dropped through the clouds. The probes and the main body –– all of which contained scientific instruments –– radioed information about the planet's atmosphere during their descent toward the surface.

A new generation of automated spacecraft –– including Magellan, Galileo, Ulysses, Mars Observer and Cassini –– is being developed and sent out into the solar system to make detailed examinations that will increase our understanding of our neighborhood and our own planet.

(Courtesy NASA/JPL).

Space History

Spacecraft Images

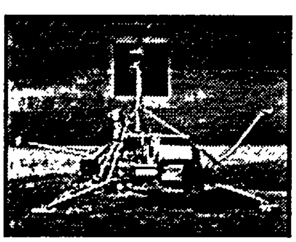


Mariner 2 (1962)

Mariner 2, the world's first successful interplanetary spacecraft, was launched August 27, 1962 and passed 34,916 kilometers (21,648 miles) from Venus on December 14, 1962. Mariner 2 measured the temperatures of the clouds and surface of Venus as well as fields and particles near the planet and in interplaentary space. Contact was lost January 3, 1963 when the spacecraft was 86.9 million kilometers (53.9 million miles) from Earth. *(Courtesy NASA/JPL).*

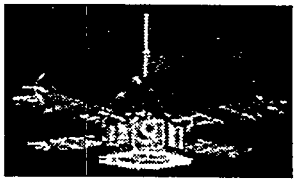
Mariner 4 (1964)

Mariner 4 was launched November 28, 1964 on a 228–day mission to Mars. The spacecraft carried instruments for eight interplanetary and planetary experiments including a TV camera. Mariner 4 passed Mars at a distance of 9,868 kilometers (6,118 miles), recording and transmitting to Earth our first close–up picture of the red planet. In 21 and a fraction of a 22nd picture, Mariner's TV camera scanned about one percent of the Martian surface, revealing ancient craters of varying size. Planetary science data, including pictures, were trasmitted over distances ranging from 215 million to 240 kilometers (134 million to 150 million miles). *(Courtesy NASA/JPL).*



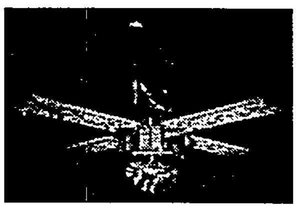
Surveyor (1966 – 1968)

A full–size engineering model of the Surveyor robotic lunar spacecraft is shown on the beach near Los Angeles, Calif. Seven Surveyors were launched toward the Moon between 1966 and 1968 to make soft landings as precursors to the Apollo astronaut missions. The successful missions and date of lunar landing were Surveyor 1 on June 2, 1966; Surveyor 3 on April 19, 1967; Surveyor 5 on September 10, 1967; Surveyor 6 on November 9, 1967; and Surveyor 7 on January 9, 1968. *(Courtesy NASA/JPL).*



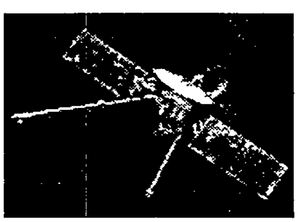
Mariner5 (1967)

The Mariner 5 spacecraft was launched June 14, 1967 and flew by Venus on October 19 of that year at a distance of 4,000 kilometers (2,480 miles). *(Courtesy NASA/JPL).*



Mariner 6 & 7 (1969)

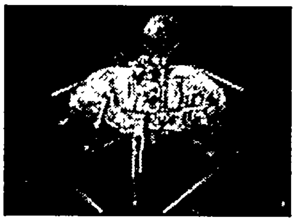
The 1969 Mars mission was conducted with Mariner 6 and 7, follow– on designs of earlier Mariners. Each spacecraft weighs 413 kilograms (910 pounds) and measures 3.35 meters (11 feet) from the scan platform to the top of the low–gain antenna. The width across the solar panels is 5.8 meters (19 feet). The eight–sided body of the spacecraft carries seven electronic compartments. A small rocket engine, used for trajectory corrections, protrudes through one of the sides. The planetary experiments aboard the spacecraft were two television cameras, an infrared radiometer, an infrared spectrometer and an ultraviolet spectrometer. The spacecraft were launched in February and March 1969, and flew past Mars in July and August 1969. *(Courtesy NASA/JPL).*



Mariner 10 (1973)

Mariner 10 used the Jet Propulsion Laboratory's basic Mariner design modified for a flight inward toward the Sun. The spacecraft weighed 503 kilograms (1,108 pounds), including 29 kilograms (64 pounds) of fuel and

30 kilograms (66 pounds) associated with the adapter between the spacecraft and the Centaur upper stage launch vehicle. Mariner 10's body was 1.39 meters (54–1/2 inches) wide and each solar panel was 2.7 meters (106 inches) long. The scientific experiments carried by the spacecraft were two television cameras, an infrared radiometer, extreme ultraviolet spectrometer, airglow instrument, magnetometer, plasma science, charged–particle telescope and radio science. Mariner 10 was launched in November 1973 and flew by Venus in January 1974. It encountered Mercury three times, in March and September of 1974 and in March 1975. *(Courtesy NASA/JPL).*



Viking (1975)

Viking was designed to orbit Mars and to land and operate on the planet's surface. Two identical spacecraft, each consisting of a lander and an orbiter, were built. NASA launched both spacecraft from Cape Canaveral, Florida — Viking 1 on August 20, 1975, and Viking 2 on September 9, 1975. The landers were sterilized before launch to prevent contamination of Mars with organisms from Earth. The spacecraft spent nearly a year cruising to Mars. Viking 1 reached Mars orbit June 19, 1976; Viking 2 began orbiting Mars August 7, 1976.

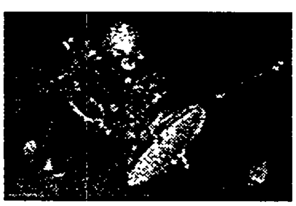
After studying orbiter photos, the Viking site certification team considered the original landing site for Viking 1 unsafe. The team examined nearby sites, and Viking 1 landed on Mars July 20, 1976, on the western slope of Chryse Planitia (the Plains of Gold) at 22.3 degrees N latitude, 48.0 degrees longitude. *(Courtesy NASA/JPL).*

Voyager (1977)

Twin Voyager spacecraft, depicted here in a full–scale model, are now traveling out of the solar system. Voyager 1, launched Sept. 5, 1977, completed its mission to Jupiter and Saturn and is now outbound from the solar system, heading in the general direction of the constellation Ophiuchus. Voyager 2 followed its sister craft to Jupiter and Saturn, then encountered Uranus and Neptune. In this view, the science boom, containing cameras and other instruments requiring maneuverability, is seen at right. The long boom at left carries two magnetic–field detectors and stretches 43 feet out from the spacecraft. The dominant feature at center, the 12–foot–diameter high–gain antenna, provides communication between the spacecraft and controllers on Earth. Just below is a shiny gold disk, a record called "Sounds of Earth," bearing messages and pictures from our planet. The Voyagers are managed for NASA by the Jet Propulsion Laboratory. *(Courtesy NASA/JPL).*

Magellan (1989)

The Magellan spacecraft is depicted in orbit around Venus. Launched in May 1989, Magellan was released in Earth orbit from a space shuttle and then injected into transfer orbit to Venus by an upper stage. During each of several cycles of 243 days each –– approximately one Venusian year –– the spacecraft used synthetic aperture radar to penetrate Venus' thick cloud cover and return maps of about 99 percent of the planet's surface. Other experiments have included measuring heights of surface features on Venus with a radar altimeter as well as studies of the planet's gravitational field. *(Courtesy NASA/JPL).*



Cassini (1997 ?)

This artist's rendering depicts the NASA/JPL Cassini spacecraft in orbit around ringed Saturn (lower right background). At the lower left, the European Space Agency's Huygens probe descends to the surface of Saturn's moon Titan (in foreground). Cassini is planned for launch on a Titan IV rocket in October 1997, with Saturn arrival in June 2004. *(Courtesy NASA/JPL).*

Space History

Chronology of Space Exploration

- **Pioneer 4** – USA Distant Lunar Flyby – 5.9 kg – (Mar 3, 1959)
  Space probe is now in solar orbit.
- **Luna 2** – USSR Lunar Hard Lander – 387 kg – (Sep 12, 1959)
  Lunar probe impacted the surface of the moon on September 15, 1959.
- **Luna 3** – USSR Lunar Far–side Flyby – 278.5 kg – (Oct 4, 1959)
  Encountered the Moon on October 7, 1959 and returned a photograph of the farside. Space probe is now in a decayed earth–moon orbit.
- **Venera 1** – USSR Venus Flyby – 643.5 kg – (Feb 12, 1961)
  Now in solar orbit.
- **Ranger 3** – USA Lunar Hard Lander – 327 kg – (Jan 26, 1962)
  Lunar probe missed the moon and is now in a solar orbit.
- **Ranger 4** – USA Lunar Hard Lander – 328 kg – (Apr 23, 1962)
  Lunar probe impacted the surface of the Moon.
- **<u>Mariner 2</u>** – USA Venus Flyby – 201 kg – (Aug 27, 1962)
  On December 14, 1962, Mariner 2 arrived and scanned the surface of Venus with infrared and microwave radiometers capturing data that proved Venus's surface to be fire–hot (about 425°C, 800°F). Three weeks after the Venus flyby Mariner 2 went off the air on Jan 3, 1963. It is now in a solar orbit.
- **Ranger 5** – USA Lunar Flyby – 340 kg – (Oct 18, 1962)
  Lunar flyby is now in a solar orbit.
- **Mars 1** – USSR Mars Probe – 893 kg – (Nov 1, 1962)
  Mars probe; failed en route.
- **Luna 4** – USSR Lunar Probe – 1,422 kg – (Apr 2, 1963)
  Lunar probe is now in an Earth Moon orbit.
- **Ranger 6** – USA Lunar Hard Lander – 361.8 kg – (Jan 30, 1964)
  Lunar probe impacted the surface of the Moon.
- **Zond 1** – USSR Venus Probe – 890 kg – (Apr 2, 1964)
  Now in solar orbit.
- **Ranger 7** – USA Lunar Hard Lander – 362 kg – (Jul 28, 1964)
  Arrived on June 28, 1964 and sent pictures back at a close range. It impacted the Moon.
- **Mariner 3** – USA Mars Flyby – 260 kg – (Nov 5, 1964)
  Mars flyby attempt now in solar orbit.
- **<u>Mariner 4</u>** – USA Mars Flyby – 260 kg – (Nov 28, 1964)
  Arrived in 1965 and returned first Mars photos. Mariner 4 is now in

a solar orbit.

- **Pioneer 6** – USA Solar Probe – 63.4 kg – (Dec 16, 1965 – Present)
  Solar probe in solar orbit is still transmitting.
- **Ranger 8** – USA Lunar Hard Lander – 366 kg – (Feb 17, 1965)
  Lunar probe sent pictures of its impact on the moon.
- **Ranger 9** – USA Lunar HARD Lander – 366 kg – (Mar 21, 1965)
  Lunar probe sent pictures of its impact on the moon.
- **Luna 5** – USSR Lunar Soft Lander – 1,474 kg – (May 9, 1965)
  The lunar soft–lander failed and impacted the moon.
- **Luna 6** – USSR Lunar Soft Lander – 1,440 kg – (Jun 8, 1965)
  Missed the moon and is now in a solar orbit.
- **Zond 3** – USSR Lunar Flyby – 959 kg – (Jul 18, 1965)
  Lunar flyby is now in a solar orbit.
- **Luna 7** – USSR Lunar Soft Lander – 1,504 kg – (Oct 4, 1965)
  Luna 7 failed and impacted the moon.
- **Venera 2** – USSR Venus Flyby – 962 kg – (Nov 12, 1965 – 1966)
  Communications failed just before arrival. Now in solar orbit.
- **Venera 3** – USSR Venus Atmospheric Probe – 958 kg – (Nov 16, 1965 – 1966)
  Communications failed just before atmosphere entry. Crashed on Venus.
- **Luna 8** – USSR Lunar Soft Lander – 1,550 kg – (Dec 3, 1965)
  Luna 8 failed and impacted the moon.
- **Luna 9** – USSR Lunar Soft Lander – 1,580 kg – (Jan 31, 1966)
  Luna 9 landed on the lunar surface and retuned photographs.
- **Luna 10** – USSR Lunar Orbiter – 1,597 kg – (Mar 31, 1966)
  Luna 10 is currently in a lunar orbit.
- **Surveyor 1** – USA Lunar Soft Lander – 269 kg – (Apr 30, 1966 to 1967)
  Surveyor 1 landed on the lunar surface.
- **Lunar Orbiter 1** – USA Lunar Orbiter – 386 kg – (Aug 10, 1966)
  Lunar Orbiter 1 orbited the moon, photographed the far side and then impacted on command.
- **Pioneer 7** – USA Solar Probe – 63 kg – (Aug 17, 1966 – ?)
  Solar probe in solar orbit was recently turned off.
- **Luna 11** – USSR Lunar Orbiter – 1,638 kg – (Aug 24, 1966)
  Luna 11 is currently in lunar orbit.
- **Surveyor 2** – USA Lunar Soft Lander – 292 kg – (Sep 20, 1966)
  Surveyor 2 failed and impacted the moon.
- **Luna 12** – USSR Lunar Orbiter – 1,620 – (Oct 22, 1966–1967)
  Luna 12 is in lunar orbit.
- **Lunar Orbiter 2** – USA Lunar Orbiter – 390 kg – (Nov 6, 1966)
  Orbited the moon, photographed the far side and potential Apollo landing sites then impacted on command.

- **Luna 13** – USSR Lunar Soft Lander – 1,700 kg – (Dec 21, 1966)
  Landed on the lunar surface.
- **Lunar Orbiter 3** – USA Lunar Orbiter – 385 kg – (Feb 5, 1967)
  Orbited the moon, photographed the far side and Apollo 12 landing site then impacted on command.
- **Surveyor 3** – USA Lunar Soft Lander – 283 kg – (Apr 17, 1967)
  Landed on the lunar surface and pieces were brought back.
- **Lunar Orbiter 4** – USA Lunar Orbiter – 390 kg – (May 4, 1967)
  Orbited the moon at a polar inclination and impacted on command.
- **Venera 4** – USSR Venus Atmospheric Probe – 1,104 kg – (Jun 12, 1967)
  First atmospheric data returned. Returned data untill crushed by the pressure on Venus.
- **Mariner 5** – USA Venus Flyby – 244 kg – (Jun 14, 1967)
  Now in solar orbit.
- **Explorer 35** – USA Lunar Orbiter – 104 kg – (Jul 19, 1967 – 1972)
  Lunar orbiter acquired field and particle data.
- **Surveyor 4** – USA Lunar Soft Lander – 283 kg – (Jul 14, 1967)
  Lander failed and impacted the moon.
- **Lunar Orbiter 5** – USA Lunar Orbiter – 389 kg (Aug 1, 1967)
  Orbited the moon at a polar inclination, took high resolution pictures of many important sites and impacted on command.
- **Surveyor 5** – USA Lunar Soft Lander – 279 kg – (Sep 8, 1967)
  Landed on the lunar surface.
- **Surveyor 6** – USA Lunar Soft Lander – 280 kg – (Nov 7, 1967)
  Landed on and took off from the lunar surface.
- **Pioneer 8** – USA Solar Probe – 63 kg – (Dec 13, 1967 – Present)
  Solar probe in solar orbit is still transmitting.
- **Surveyor 7** – USA Lunar Soft Lander – 1,036 kg – (Jan 7, 1968)
  Landed on the lunar surface.
- **Luna 14** – USSR Lunar Probe – 1,700 kg – (Apr 7, 1968)
  Luna 14 is in a lunar–solar orbit.
- **Zond 5** – USSR Lunar Flyby – 5,375 kg – (Sep 14, 1968)
  Lunar fly–around and earth return.
- **Pioneer 9** – USA Solar Probe – 63 kg – (Nov 8, 1968 – Mar 3, 1987)
  In solar orbit. Died on March 3, 1987.
- **Zond 6** – USSR Lunar Flyby – 5,375 – (Nov 10, 1968)
  Lunar fly–around and earth return.
- **Apollo 8** – USA Lunar Manned Orbiter – 28,883 kg – (Dec 21, 1968)
  First manned lunar fly–around and Earth return.
- **Venera 5** – USSR Venus Atmosphere Probe – 1,128 kg – (Jan 5, 1969)
  Returned data down to within 26 km of surface. Returned data untill crushed by the pressure on Venus.
- **Venera 6** – USSR Venus Atmosphere Probe – 1,128 kg – (Jan 10, 1969)

Returned data down to within 11 km of surface. Returned data untill crushed by the pressure on Venus.

- **Mariner 6** – USA Mars Flyby – 412 kg – (Feb 24, 1969)
  Probe is now in a solar orbit.
- **Mariner 7** – USA Mars Flyby – 412 kg – (Mar 27, 1969)
  Probe is now in a solar orbit.
- **Apollo 10** – USA Lunar Manned Orbiter – 42,530 kg – (May 18, 1969)
  Manned lunar fly–around and Earth return.
- **Luna 15** – USSR Lunar Lander – 2,718 kg – (Jul 13, 1969)
  Unsuccessful sample return attempt. Crashed during landing.
- **Apollo 11** – USA Lunar Manned Lander – 43,811 kg – (Jul 16, 1969)
  Apollo 11 was the first manned lunar landing which took place on July 20, 1969. The landing site was *Mare Tranquillitatis* at latitude 0°67' N and longitude 23°49' E. Samples amounting to 21.7 kg were returned from the moon.
- **Zond 7** – USSR Lunar Flyby – 5,979 kg – (Aug 8, 1969)
  Lunar fly–around and Earth return.
- **Apollo 12** – USA Lunar Manned Lander – 43,848 kg – (Nov 14, 1969)
  Apollo 12 was a manned lunar landing which took place on November 19, 1969. The landing site was *Oceanus Procellarum* at latitude 3°12' S and longitude 23°23' W. Samples amounting to 34.4 kg were returned from the moon.
- **Apollo 13** – USA Lunar Flyby – 43,924 kg – (Apr 11, 1969)
- **Venera 7** – USSR Venus Lander – 1180 kg – (Aug 17, 1970)
  First successful landing of a spacecraft on another planet. Sent back data for 23 minutes.
- **Luna 16** – USSR Lunar Lander – 5,600 kg – (Sep 12, 1970)
  Landed on September 20, 1970 at *Mare Fecunditaits* located at latitude 0°41' S and longitude 56°18' E. 100 gm of lunar samples were returned to the Earth.
- **Luna 17** – USSR Lunar Lander and Rover – 5,600 – (Nov 10, 1970 – 1971)
  Made lunar landing with an automated **Lunokhod 1** Rover.
- **Apollo 14** – USA Lunar Manned Lander – 44,456 kg – (Jan 31, 1971)
  Landed on the moon on Feb 5, 1971 at *Fra Mauro* located at 3°40' S and longitude 17°28' E. 42.9 kg of lunar samples were returned.
- **Mars 2** – USSR Mars Orbiter – 4,650 kg – (May 19, 1971)
  Returned data until 1972.
- **Mars 2** – USSR Mars Soft Lander – (May 19, 1971)
  Crashed, first human artifact on Mars. No planetary data returned.
- **Mars 3** – USSR Mars Orbiter – 4,643 kg – (May 28, 1971)
  Returned data until Aug 1972.
- **Mars 3** – USSR Mars Soft Lander – (May 28, 1971)
  Successfully landed but only returned data for 90 seconds.

- **Mariner 9** – USA Mars Orbiter – 974 kg – (May 30, 1971 – 1972)
  Entered orbit on November 14, 1971. This successful orbiter is still in Mars orbit.
- **Apollo 15** – USA Lunar Manned Lander – 46,723 kg – (Jul 26, 1971)
  Landed on the moon on Jul 30, 1971. The landing site was *Hadley–Apennine* at latitude 26°6' N and longitude 3°39' E. Samples amounting to 76.8 kg were returned from the moon.
- **Luna 18** – USSR Lunar Lander – 5,600 kg – (Sep 2, 1971 – 1972)
  Unsuccessful sample return attempt. Crashed during landing.
- **Luna 19** – USSR Lunar Orbiter – 5,600 kg – (Sep 28, 1971 – 1972)
  The orbiter is now an a lunar orbit.
- **Luna 20** – USSR Lunar Lander – 5,600 kg – (Feb 14, 1972)
  Landed on the moon and returned samples to the Earth. Landed on February 21, 1972 at *Apollonius highlands* located at latitude 3°32' N and longitude 56°33' E. 30 gm of lunar samples were returned to the Earth.
- **Pioneer 10** – USA Jupiter Flyby – 259 kg – (Mar 3, 1972)
  Flew by Jupiter on Dec 1, 1973 and then left the solar system. The orbit boundry of Pluto was crossed on Jun 13, 1983.
- **Venera 8** – USSR Venus Lander – 1,180 kg – (Mar 27, 1972)
  Returned data for 50 minutes.
- **Apollo 16** – USA Manned Lunar Lander – 46,733 kg – (Apr 16, 1972)
  Landed on the moon on Apr 21, 1972 at the *Descartes* crater located at latitude 9°00' N and longitude 15°31' E. 94.7 kg of lunar samples were returned.
- **Apollo 17** – USA Manned Lunar Lander – 46,743 kg – (Dec 7, 1972)
  Landed on the moon on Dec 12, 1972. The landing site was *Taurus–Littrow* at latitude 20°10' N and longitude 30°46' E. Samples amounting to 110.5 kg were returned from the moon.
- **Luna 21** – USAR Lunar Lander and Rover – 4,850 kg – (Jan 8, 1973)
  Made lunar landing with an automated **Lunokhod 2** Rover.
- **Pioneer 11** – USA Flyby – 259 kg – (Apr 6, 1973)
  Flew by Jupiter on December 1, 1974 and Saturn on September 1, 1979 then left the solar system.
- **Explorer 49** – USA Solar Probe – 328 kg – (Jun 10, 1973)
  Solar physics probe placed in lunar orbit.
- **Mars 4** – USSR Mars Orbiter – 4,650 kg – (Jul 21, 1973)
  Failed to enter Mars orbit and became a flyby, but returned some images and data.
- **Mars 5** – USSR Mars Orbiter – 4,650 kg – (Jul 25, 1973)
- **Mars 6** – USSR Mars Soft Lander – 4,650 kg – (Aug 5, 1973)
  Returned descent data, then crashed.
- **Mars 7** – USSR Mars Flyby & Soft Lander – 4,650 kg – (Aug 9, 1973)

Lander missed Mars. Carrier and lander are now in solar orbit.

- **Mariner 10** – USA Lunar Flyby – 526 kg – (Nov 3, 1973)
  Mariner was a Venus/Mercury flyby and is now in solar orbit.
- **Luna 22** – USSR Lunar Orbiter – 5,600 kg – (May 29, 1974 – 1975)
  Successfully entered lunar orbit.
- **Luna 23** – USSR Lunar Probe – 5,6000 kg – (Oct 28, 1974)
  Crashed on the lunar surface.
- **Helios** – USA & West Germany Solar Probe – 370 kg – (Dec 10, 1974 – 1975)
  Solar probe is in a solar orbit.
- **Venera 9** – USSR Venus Orbiter – 4,936 kg (Jun 8, 1975)
  Venus probe in Venus orbit.
- **Venera 10** – USSR Venus Orbiter – 5,033 kg – (Jun 14, 1975)
- **Viking 1** – USA Mars Orbiter & Lander – 3,399 kg – (Aug 20, 1975 – 1980)
  Successful orbiter and lander. Went into orbit on June 19, 1976. The lander touched down on Mars on July 20, 1976.
- **Viking 2** – USA Mars Orbiter & Lander – 3,399 kg – (Sep 9, 1975 – 1978)
  Successful orbiter and lander. Went into orbit on July 24, 1976. The lander touched down on Mars on August 7, 1976.
- **Venera 9** – USSR Venus Lander – (Landed: Nov 22, 1975)
  Returned the first image from surface of another planet.
- **Venera 10** – USSR Venus Lander – (Landed: Nov 25, 1975)
  Returned an image and 65 minutes of data from the surface of Venus.
- **Luna 24** – USSR Lunar Lander – 4,800 kg – (Aug 9, 1976)
  The landing site was *Mare Crisium* at latitude 12°45' N and longitude 60°12' E. Samples amounting to 170 gm were returned from the moon.
- **Voyager 1** – USA Flyby – 800 kg – (Sep 5, 1977)
  Voyager 1 flew by Jupiter on March 5, 1979 and Saturn on November 12, 1980.
- **Voyager 2** – USA Flyby – 800 kg – (Aug 20, 1977)
  Voyager 2 flew by Jupiter on July 9, 1979, Saturn on August 26, 1981, Uranus on January 24, 1986, and Neptune on August 24, 1989.
- **Pioneer 12** – USA Venus Orbiter – 582 kg – (May 20, 1978 – 1992)
  Also known as **Pioneer Venus Orbiter**.
- **Pioneer 13** – USA Venus Atmosphere Probe – 904 kg – (Aug 8, 1978)
  Multi–probe of Venus atmosphere. Entered atmosphere Dec 9, 1978.
- **International Sun–Earth Explorer 3** – USA – 479 kg – (Aug 12, 1978)
  Flew by Comet Giacobini–Zinner on Sep 11, 1985. Renamed **International Cometary Explorer**

- **Venera 11** – USSR Venus Lander – 4,940 kg – (Sep 9, 1978)
  Landed on Dec 21, 1978 and returned data for 95 minutes.
- **Venera 12** – USSR Venus Lander – 4,940 kg – (Sep 14, 1978)
  Landed on Dec 21, 1978 and returned data for 110 minutes.
- **Venera 13** – USSR Venus Lander – 5,000 kg – (Oct 30, 1981)
  Landed on Mar 1, 1982. Returned first color picture from Venus surface.
- **Venera 14** – USSR Venus Lander – 5,000 kg – (Nov 4, 1981)
  Landed on Mar 1, 1982. Returned a color picture of surface.
- **Venera 15** – USSR Venus Orbiter – 5,000 kg – (Jun 2, 1983)
  Radar mapping mission. Arrived at Venus on Oct 10, 1983.
- **Venera 16** – USSR Venus Orbiter – 5,000 kg – (Jun 7, 1983)
  Radar mapping mission. Arrived at Venus on Oct 14, 1983.
- **Vega 1** – USSR Venus/Comet Halley Flyby – 4,000 kg – (Dec 15, 1984)
  Venus/Comet Halley probe now in solar orbit. Comet Halley flyby took place on Mar 6, 1986.
- **Vega 2** – USSR Venus/Comet Halley Probe – 4,000 kg – (Dec 21, 1984)
  Venus/Comet Halley probe now in solar orbit. Released an atmospheric baloon probe on Venus in 1985. Comet Halley flyby took place on Mar 9, 1986.
- **Sakigake** – Japan – 141 kg – (Jan 7, 1985)
  Comet Halley flyby took place on Mar 1, 1986.
- **Giotto** – Europe – 512 kg – (Jul 2, 1985)
  Comet Halley flyby took place on Mar 13, 1986.
- **Suisei** – Japan – 141 kg – (Aug 18, 1985)
  Comet Halley flyby took place on Mar 8, 1986.
- **Phobos 1** – USSR Mars Orbiter – 5,000 kg – (Jul 7, 1988)
  Lost through a command error on September 2, 1988.
- **Phobos 2** – USSR Mars Orbiter – 5,000 kg – (Jul 12, 1988)
  Mars orbiter and Phobos lander. Was inserted into orbit on January 30, 1989.
- **Magellan** – USA Venus Orbiter – 3,545 kg – (May 4, 1989 – Present)
  Magellan was launched on May 4, 1989. It was released in Earth orbit from a space shuttle and then inject into a transer orbit to Venus by an upper stage. Its primary mission is to map Venus using synthetic aperture radar. The surface of Venus is obscured by thick clouds of carbon dioxide which makes the suface invisible to optical instruments.
- **Galileo** – USA & Europe Flybys – 2,222 kg – (Oct 18, 1989)
  Galileo was designed to study Jupiter's atmosphere, satellites and surrounding magnetosphere for 2 years. In order to get there, it used gravity assist techniques to pick up speed by flying by Venus on February 10, 1990. It then flew by the Earth & Moon twice. The

first was on December 8, 1990 and the second December 8, 1992. It has made encounters asteroid 951 Gaspra on October 29, 1991 and asteroid 243 Ida on August 28, 1993.

- **Muses–A** – Japan Lunar Orbiters – (1990)
  This consisted of two small orbiters but failed to send back data from their orbit around the Moon. This was the first non USA or USSR probe to reach Moon.
- **Ulysses** – USA & Europe Solar Flyby – 370 kg – (Oct 6, 1990)
  The Ulysses spacecraft is an international project to study the poles of the sun and interstellar space above and below the poles. It used Jupiter as a gravity assit to swing out of the ecliptic plane and onward to the poles of the sun. The Jupiter flyby was on February 8, 1992. The first solar polar passage will be in June 1994 and the spacecraft will pass the solar equator in February 1995.
- **Mars Observer** – USA Mars Orbiter (Sep 25, 1992)
  Approach observations only. Failed to go into orbit.
- **Clementine** – USA Lunar Orbiter – (1994)

Chronology of Space Exploration

Contents

Sun

- **Pioneer 6** – USA Solar Probe – 63.4 kg – (Dec 16, 1965 – Present)
  Solar probe in solar orbit is still transmitting.
- **Pioneer 7** – USA Solar Probe – 63 kg – (Aug 17, 1966 – ?)
  Solar probe in solar orbit was recently turned off.
- **Pioneer 8** – USA Solar Probe – 63 kg – (Dec 13, 1967 – Present)
  Solar probe in solar orbit is still transmitting.
- **Pioneer 9** – USA Solar Probe – 63 kg – (Nov 8, 1968 – Mar 3, 1987)
  In solar orbit. Died on March 3, 1987.
- **Explorer 49** – USA Solar Probe – 328 kg – (Jun 10, 1973)
  Solar physics probe placed in lunar orbit.
- **Helios** – USA & West Germany – 370 kg – (Dec 10, 1974 – 1975)
  Solar probe is in a solar orbit.
- **Ulysses** – USA & Europe Flyby – 370 kg – (Oct 6, 1990)
  The Ulysses spacecraft is an international project to study the poles of the sun and interstellar space above and below the poles. It used Jupiter as a gravity assit to swing out of the ecliptic plane and onward to the poles of the sun. The Jupiter flyby was on February 8, 1992. The first solar polar passage will be in June 1994 and the spacecraft will pass the solar equator in February 1995.

Mercury

- Mariner 10 – USA Flyby – Nov 3, 1973 – (Nov 3, 1973)
  Venus and Mercury (1974) flyby and is now in a solar orbit.

Venus

- **Venera 1** – USSR Flyby – 643.5 kg – (Feb 12, 1961)
  Now in solar orbit.
- **Mariner 2** – USA Flyby – 201 kg – (Aug 27, 1962)
  On December 14, 1962, Mariner 2 arrived and scanned the surface of Venus with infrared and microwave radiometers capturing data that proved Venus's surface to be fire–hot (about 425°C, 800°F). Three weeks after the Venus flyby Mariner 2 went off the air on Jan 3, 1963. It is now in a solar orbit.
- **Zond 1** – USSR Probe – 890 kg – (Apr 2, 1964)
  Now in solar orbit.
- **Venera 2** – USSR Flyby – 962 kg – (Nov 12, 1965 – 1966)
  Communications failed just before arrival. Now in solar orbit.
- **Venera 3** – USSR Atmospheric Probe – 958 kg – (Nov 16, 1965 – 1966)
  Communications failed just before atmosphere entry. Crashed on Venus.
- **Venera 4** – USSR Atmospheric Probe – 1,104 kg – (Jun 12, 1967)
  First atmospheric data returned. Returned data untill crushed by the pressure on Venus.
- **Mariner 5** – USA Flyby – 244 kg – (Jun 14, 1967)
  Now in solar orbit.
- **Venera 5** – USSR Atmosphere Probe – 1,128 kg – (Jan 5, 1969)
  Returned data down to within 26 km of surface. Returned data untill crushed by the pressure on Venus.
- **Venera 6** – USSR Atmosphere Probe – 1,128 kg – (Jan 10, 1969)
  Returned data down to within 11 km of surface. Returned data untill crushed by the pressure on Venus.
- **Venera 7** – USSR Lander – 1180 kg – (Aug 17, 1970)
  First successful landing of a spacecraft on another planet. Sent back data for 23 minutes.
- **Venera 8** – USSR Lander – 1,180 kg – (Mar 27, 1972)
  Returned data for 50 minutes.
- **Mariner 10** – USA Flyby – 526 kg – (Nov 3, 1973)
  Venus/Mercury flyby. Now in solar orbit.
- **Venera 9** – USSR Orbiter – 4,936 kg (Jun 8, 1975)
  Venus probe in Venus orbit.

- **Venera 9** – USSR Lander – (Landed: Nov 22, 1975)
  Returned the first image from surface of another planet.
- **Venera 10** – USSR Orbiter – 5,033 kg – (Jun 14, 1975)
- **Venera 10** – USSR Lander – (Landed: Nov 25, 1975)
  Returned an image and 65 minutes of data from the surface of Venus.
- **Pioneer 12** – USA Orbiter – 582 kg – (May 20, 1978 – 1992)
  Also known as **Pioneer Venus Orbiter**.
- **Pioneer 13** – USA Atmosphere Probe – 904 kg – (Aug 8, 1978)
  Multi–probe of Venus atmosphere. Entered atmosphere Dec 9, 1978.
- **Venera 11** – USSR Lander – 4,940 kg – (Sep 9, 1978)
  Landed on Dec 21, 1978 and returned data for 95 minutes.
- **Venera 12** – USSR Lander – 4,940 kg – (Sep 14, 1978)
  Landed on Dec 21, 1978 and returned data for 110 minutes.
- **Venera 13** – USSR Lander – 5,000 kg – (Oct 30, 1981)
  Landed on Mar 1, 1982. Returned first color picture from Venus surface.
- **Venera 14** – USSR Lander – 5,000 kg – (Nov 4, 1981)
  Landed on Mar 1, 1982. Returned a color picture of surface.
- **Venera 15** – USSR Orbiter – 5,000 kg – (Jun 2, 1983)
  Radar mapping mission. Arrived at Venus on Oct 10, 1983.
- **Venera 16** – USSR Orbiter – 5,000 kg – (Jun 7, 1983)
  Radar mapping mission. Arrived at Venus on Oct 14, 1983.
- **Vega 1** – USSR Flyby – 5,000 kg – (Dec 15, 1984)
  Venus/Comet Halley probe now in solar orbit.
- **Vega 2** – USSR Probe – 5,000 kg – (Dec 21, 1984)
  Venus/Comet Halley probe now in solar orbit. Released an atmospheric baloon probe on Venus in 1985.
- **Galileo** – USA & Europe Flyby – 2,222 kg – (Oct 18, 1989)
  Closest approach to Venus was on February 10, 1990.
- **Magellan** – USA Orbiter – 3,545 kg – (May 4, 1989 – Present)
  Magellan was launched on May 4, 1989. It was released in Earth orbit from a space shuttle and then inject into a transer orbit to Venus by an upper stage. Its primary mission is to map Venus using synthetic aperture radar. The surface of Venus is obscured by thick clouds of carbon dioxide which makes the suface invisible to optical instruments.

Moon

- **Pioneer 4** – USA Distant Flyby – 5.9 kg – (Mar 3, 1959)
  Space probe is now in solar orbit.
- **Luna 2** – USSR Hard Lander – 387 kg – (Sep 12, 1959)
  Lunar probe impacted the surface of the moon on September 15, 1959.
- **Luna 3** – USSR Far–side Flyby – 278.5 kg – (Oct 4, 1959)
  Encountered the Moon on October 7, 1959 and returned a photograph of the farside. Space probe is now in a decayed earth–moon orbit.
- **Ranger 3** – USA Hard Lander – 327 kg – (Jan 26, 1962)
  Lunar probe missed the moon and is now in a solar orbit.
- **Ranger 4** – USA Hard Lander – 328 kg – (Apr 23, 1962)
  Lunar probe impacted the surface of the Moon.
- **Ranger 5** – USA Lunar Flyby – 340 kg – (Oct 18, 1962)
  Lunar flyby is now in a solar orbit.
- **Luna 4** – USSR – 1,422 kg – (Apr 2, 1963)
  Lunar probe is now in an Earth Moon orbit.
- **Ranger 6** – USA Hard Lander – 361.8 kg – (Jan 30, 1964)
  Lunar probe impacted the surface of the Moon.
- **Ranger 7** – USA Hard Lander – 362 kg – (Jul 28, 1964)
  Arrived on June 28, 1964 and sent pictures back at a close range. It impacted the Moon.
- **Ranger 8** – USA Hard Lander – 366 kg – (Feb 17, 1965)
  Lunar probe sent pictures of its impact on the moon.
- **Ranger 9** – USA HARD Lander – 366 kg – (Mar 21, 1965)
  Lunar probe sent pictures of its impact on the moon.
- **Luna 5** – USSR Soft Lander – 1,474 kg – (May 9, 1965)
  The lunar soft–lander failed and impacted the moon.
- **Luna 6** – USSR Soft Lander – 1,440 kg – (Jun 8, 1965)
  Missed the moon and is now in a solar orbit.
- **Zond 3** – USSR Flyby – 959 kg – (Jul 18, 1965)
  Lunar flyby is now in a solar orbit.
- **Luna 7** – USSR Soft Lander – 1,504 kg – (Oct 4, 1965)
  Luna 7 failed and impacted the moon.
- **Luna 8** – USSR Soft Lander – 1,550 kg – (Dec 3, 1965)
  Luna 8 failed and impacted the moon.
- **Luna 9** – USSR Soft Lander – 1,580 kg – (Jan 31, 1966)
  Luna 9 landed on the lunar surface and retuned photographs.
- **Luna 10** – USSR Orbiter – 1,597 kg – (Mar 31, 1966)
  Luna 10 is currently in a lunar orbit.
- <u>**Surveyor 1**</u> – USA Soft Lander – 269 kg – (Apr 30, 1966 to 1967)
  Surveyor 1 landed on the lunar surface.
- **Lunar Orbiter 1** – USA Orbiter – 386 kg – (Aug 10, 1966)

Lunar Orbiter 1 orbited the moon, photographed the far side and then impacted on command.

- **Luna 11** – USSR Orbiter – 1,638 kg – (Aug 24, 1966)
  Luna 11 is currently in lunar orbit.
- **Surveyor 2** – USA Soft Lander – 292 kg – (Sep 20, 1966)
  Surveyor 2 failed and impacted the moon.
- **Luna 12** – USSR Orbiter – 1,620 – (Oct 22, 1966–1967)
  Luna 12 is in lunar orbit.
- **Lunar Orbiter 2** – USA Orbiter – 390 kg – (Nov 6, 1966)
  Orbited the moon, photographed the far side and potential Apollo landing sites then impacted on command.
- **Luna 13** – USSR Soft Lander – 1,700 kg – (Dec 21, 1966)
  Landed on the lunar surface.
- **Lunar Orbiter 3** – USA Orbiter – 385 kg – (Feb 5, 1967)
  Orbited the moon, photographed the far side and Apollo 12 landing site then impacted on command.
- **Surveyor 3** – USA Soft Lander – 283 kg – (Apr 17, 1967)
  Landed on the lunar surface and pieces were brought back.
- **Lunar Orbiter 4** – USA Orbiter – 390 kg – (May 4, 1967)
  Orbited the moon at a polar inclination and impacted on command.
- **Explorer 35** – USA Orbiter – 104 kg – (Jul 19, 1967 – 1972)
  Lunar orbiter acquired field and particle data.
- **Surveyor 4** – USA Soft Lander – 283 kg – (Jul 14, 1967)
  Lander failed and impacted the moon.
- **Lunar Orbiter 5** – USA Orbiter – 389 kg (Aug 1, 1967)
  Orbited the moon at a polar inclination, took high resolution pictures of many important sites and impacted on command.
- **Surveyor 5** – USA Soft Lander – 279 kg – (Sep 8, 1967)
  Landed on the lunar surface.
- **Surveyor 6** – USA Soft Lander – 280 kg – (Nov 7, 1967)
  Landed on and took off from the lunar surface.
- **Surveyor 7** – USA Soft Lander – 1,036 kg – (Jan 7, 1968)
  Landed on the lunar surface.
- **Luna 14** – USSR – 1,700 kg – (Apr 7, 1968)
  Luna 14 is in a lunar–solar orbit.
- **Zond 5** – USSR Flyby – 5,375 kg – (Sep 14, 1968)
  Lunar fly–around and earth return.
- **Zond 6** – USSR Flyby – 5,375 – (Nov 10, 1968)
  Lunar fly–around and earth return.
- **Apollo 8** – USA Manned Orbiter – 28,883 kg – (Dec 21, 1968)
  First manned lunar fly–around and Earth return.
- **Apollo 10** – USA Manned Orbiter – 42,530 kg – (May 18, 1969)
  Manned lunar fly–around and Earth return.

- **Luna 15** – USSR Lander – 2,718 kg – (Jul 13, 1969)
  Unsuccessful sample return attempt. Crashed during landing.
- **Apollo 11** – USA Manned Lander – 43,811 kg – (Jul 16, 1969)
  Apollo 11 was the first manned lunar landing which took place on July 20, 1969. The landing site was *Mare Tranquillitatis* at latitude 0°67' N and longitude 23°49' E. Samples amounting to 21.7 kg were returned from the moon.
- **Zond 7** – USSR Flyby – 5,979 kg – (Aug 8, 1969)
  Lunar fly--around and Earth return.
- **Apollo 12** – USA Manned Lander – 43,848 kg – (Nov 14, 1969)
  Apollo 12 was a manned lunar landing which took place on November 19, 1969. The landing site was *Oceanus Procellarum* at latitude 3°12' S and longitude 23°23' W. Samples amounting to 34.4 kg were returned from the moon.
- **Apollo 13** – USA Flyby – 43,924 kg – (Apr 11, 1969)
- **Luna 16** – USSR Lander – 5,600 kg – (Sep 12, 1970)
  Landed on September 20, 1970 at *Mare Fecunditaits* located at latitude 0°41' S and longitude 56°18' E. 100 gm of lunar samples were returned to the Earth.
- **Luna 17** – USSR Lander and Rover – 5,600 – (Nov 10, 1970 – 1971)
  Made lunar landing with an automated **Lunokhod 1** Rover.
- **Apollo 14** – USA Manned Lander – 44,456 kg – (Jan 31, 1971)
  Landed on the moon on Feb 5, 1971 at *Fra Mauro* located at 3°40' S and longitude 17°28' E. 42.9 kg of lunar samples were returned.
- **Apollo 15** – USA Manned Lander – 46,723 kg – (Jul 26, 1971)
  Landed on the moon on Jul 30, 1971. The landing site was *Hadley–Apennine* at latitude 26°6' N and longitude 3°39' E. Samples amounting to 76.8 kg were returned from the moon.
- **Luna 18** – USSR Lander – 5,600 kg – (Sep 2, 1971 – 1972)
  Unsuccessful sample return attempt. Crashed during landing.
- **Luna 19** – USSR Orbiter – 5,600 kg – (Sep 28, 1971 – 1972)
  The orbiter is now an a lunar orbit.
- **Luna 20** – USSR Lander – 5,600 kg – (Feb 14, 1972)
  Landed on the moon and returned samples to the Earth. Landed on February 21, 1972 at *Apollonius highlands* located at latitude 3°32' N and longitude 56°33' E. 30 gm of lunar samples were returned to the Earth.
- **Apollo 16** – USA Manned Lander – 46,733 kg – (Apr 16, 1972)
  Landed on the moon on Apr 21, 1972 at the *Descartes* crater located at latitude 9°00' N and longitude 15°31' E. 94.7 kg of lunar samples were returned.
- **Apollo 17** – USA Manned Lander – 46,743 kg – (Dec 7, 1972)

Landed on the moon on Dec 12, 1972. The landing site was *Taurus–Littrow* at latitude 20°10' N and longitude 30°46' E. Samples amounting to 110.5 kg were returned from the moon.

- **Luna 21** – USAR Lander and Rover – 4,850 kg – (Jan 8, 1973)
  Made lunar landing with an automated **Lunokhod 2** Rover.
- **Mariner 10** – USA Flyby – 526 kg – (Nov 3, 1973)
  Mariner was a Venus/Mercury flyby and is now in solar orbit.
- **Luna 22** – USSR Orbiter – 5,600 kg – (May 29, 1974 – 1975)
  Successfully entered lunar orbit.
- **Luna 23** – USSR Lunar Probe – 5,6000 kg – (Oct 28, 1974)
  Crashed on the lunar surface.
- **Luna 24** – USSR Lunar Lander – 4,800 kg – (Aug 9, 1976)
  The landing site was *Mare Crisium* at latitude 12°45' N and longitude 60°12' E. Samples amounting to 170 gm were returned from the moon.
- **Muses–A** – Japan Orbiters – (1990)
  This consisted of two small orbiters but failed to send back data from their orbit around the Moon. This was the first non USA or USSR probe to reach Moon.
- **Galileo** – USA & Europe Flybys – 2,222 kg – (Oct 18, 1989)
  Galileo made two approaches of the Earth and Moon. The first was on December 8, 1990 and the second December 8, 1992.
- **Clementine** – USA Orbiter – (1994)

Mars

- **Mars 1** – USSR Probe – 893 kg – (Nov 1, 1962)
  Mars probe; failed en route.
- **Mariner 3** – USA Flyby – 260 kg – (Nov 5, 1964)
  Mars flyby attempt now in solar orbit.
- **Mariner 4** – USA Flyby – 260 kg – (Nov 28, 1964)
  Arrived in 1965 and returned first Mars photos. Mariner 4 is now in a solar orbit.
- **Mariner 6** – USA Flyby – 412 kg – (Feb 24, 1969)
  Probe is now in a solar orbit.
- **Mariner 7** – USA Flyby – 412 kg – (Mar 27, 1969)
  Probe is now in a solar orbit.
- **Mars 2** – USSR Orbiter – 4,650 kg – (May 19, 1971)
  Returned data until 1972.
- **Mars 2** – USSR Soft Lander – (May 19, 1971)
  Crashed, first human artifact on Mars. No planetary data returned.

- **Mars 3** – USSR Orbiter – 4,643 kg – (May 28, 1971)
  Returned data until Aug 1972.
- **Mars 3** – USSR Soft Lander – (May 28, 1971)
  Successfully landed but only returned data for 90 seconds.
- **Mariner 9** – USA Orbiter – 974 kg – (May 30, 1971 – 1972)
  Entered orbit on November 14, 1971. This successful orbiter is still in Mars orbit.
- **Mars 4** – USSR Orbiter – 4,650 kg – (Jul 21, 1973)
  Failed to enter Mars orbit and became a flyby, but returned some images and data.
- **Mars 5** – USSR Orbiter – 4,650 kg – (Jul 25, 1973)
- **Mars 6** – USSR Soft Lander – 4,650 kg – (Aug 5, 1973)
  Returned descent data, then crashed.
- **Mars 7** – USSR Flyby & Soft Lander – 4,650 kg – (Aug 9, 1973)
  Lander missed Mars. Carrier and lander are now in solar orbit.
- **Viking 1** – USA Orbiter & Lander – 3,399 kg – (Aug 20, 1975 – 1980)
  Successful orbiter and lander. Went into orbit on June 19, 1976. The lander touched down on Mars on July 20, 1976.
- **Viking 2** – USA Orbiter & Lander – 3,399 kg – (Sep 9, 1975 – 1978)
  Successful orbiter and lander. Went into orbit on July 24, 1976. The lander touched down on Mars on August 7, 1976.
- **Phobos 1** – USSR Orbiter – 5,000 kg – (Jul 7, 1988)
  Lost through a command error on September 2, 1988.
- **Phobos 2** – USSR Orbiter – 5,000 kg – (Jul 12, 1988)
  Mars orbiter and Phobos lander. Was inserted into orbit on January 30, 1989.
- **Mars Observer** – USA Orbiter (Sep 25, 1992)
  Approach observations only. Failed to go into orbit.

Jupiter

- **Pioneer 10** – USA Flyby – 259 kg – (Mar 3, 1972)
  Flew by Jupiter on Dec 1, 1973 and then left the solar system. The orbit boundry of Pluto was crossed on Jun 13, 1983.
- **Pioneer 11** – USA Flyby – 259 kg – (Apr 6, 1973)
  Flew by Jupiter on December 1, 1974 and Saturn on September 1, 1979 then left the solar system.
- **Voyager 1** – USA Flyby – 800 kg – (Sep 5, 1977)
  Voyager 1 flew by Jupiter on March 5, 1979 and Saturn on November 12, 1980.
- **Voyager 2** – USA Flyby – 800 kg – (Aug 20, 1977)

Voyager 2 flew by Jupiter on July 9, 1979, Saturn on August 26, 1981, Uranus on January 24, 1986, and Neptune on August 24, 1989.

- **Ulysses** – USA & Europe Flyby – 370 kg – (Oct 6, 1990)
  The Ulysses spacecraft is an international project to study the poles of the sun and interstellar space above and below the poles. It used Jupiter for gravity assit to swing out of the ecliptic plane and onward to the poles of the sun. The Jupiter flyby was on February 8, 1992. The first solar polar passage will be in June 1994 and the spacecraft will pass the solar equator in February 1995.
- **Galileo** – USA & Europe Flybys – 2,222 kg – (Oct 18, 1989)
  Galileo was designed to study Jupiter's atmosphere, satellites and surrounding magnetosphere for 2 years. In order to get there, it used gravity assist techniques to pick up speed by flying by Venus on February 10, 1990. It then flew by the Earth twice. The first was on December 8, 1990 and the second December 8, 1992.

Saturn

- **Pioneer 11** – USA Flyby – 259 kg – (Apr 6, 1973)
  Flew by Jupiter on December 1, 1974 and Saturn on September 1, 1979 then left the solar system.
- **Voyager 1** – USA Flyby – 800 kg – (Sep 5, 1977)
  Voyager 1 flew by Jupiter on March 5, 1979 and Saturn on November 12, 1980.
- **Voyager 2** – USA Flyby – 800 kg – (Aug 20, 1977)
  Voyager 2 flew by Jupiter on July 9, 1979, Saturn on August 26, 1981, Uranus on January 24, 1986, and Neptune on August 24, 1989.

Uranus

- **Voyager 2** – USA Flyby – 800 kg – (Aug 20, 1977)
  Voyager 2 flew by Jupiter on July 9, 1979, Saturn on August 26, 1981, Uranus on January 24, 1986, and Neptune on August 24, 1989.

Neptune

- **Voyager 2** – USA Flyby – 800 kg – (Aug 20, 1977)
  Voyager 2 flew by Jupiter on July 9, 1979, Saturn on August 26, 1981, Uranus on January 24, 1986, and Neptune on August 24, 1989.

Pluto

- **None**

- **Pluto Fast Flyby** – (1999–2001)
  A small, fast, relatively cheep flyby of the planet Pluto is being planned for possible launch in 1999–2001. If this launch date is achieved then the spacecraft would pass within 15,000 km of Pluto and Charon between the years of 2007 and 2010.

Asteroids

Gaspra:

- **Galileo** – USA & Europe Flybys – 2,222 kg – (Oct 18, 1989)
  Galileo made its closest approach to asteroid 951 Gaspra on October 29, 1991.

Ida:

- **Galileo** – USA & Europe Flybys – 2,222 kg – (Oct 18, 1989)
  Galileo made its closest approach to asteroid 243 Ida on August 28, 1993.

Comets

Giacobini–Zinner:

- **International Sun–Earth Explorer 3** – USA – 479 kg – (Aug 12, 1978)
  Flew by Comet Giacobini–Zinner on Sep 11, 1985. Renamed **International Cometary Explorer**

Halley:

- **Vega 1** – USSR Flyby – 4,000 kg – (Dec 15, 1984)
  Venus/Comet Halley probe now in solar orbit. Comet Halley flyby took place on Mar 6, 1986.
- **Vega 2** – USSR Probe – 4,000 kg – (Dec 21, 1984)
  Venus/Comet Halley probe now in solar orbit. Released an atmospheric baloon probe on Venus in 1985. Comet Halley flyby took place on Mar 9, 1986.
- **Sakigake** – Japan – 141 kg – (Jan 7, 1985)
  Comet Halley flyby took place on Mar 1, 1986.
- **Giotto** – Europe – 512 kg – (Jul 2, 1985)
  Comet Halley flyby took place on Mar 13, 1986.
- **Suisei** – Japan – 141 kg – (Aug 18, 1985)
  Comet Halley flyby took place on Mar 8, 1986.

Solar System Home

Planets & Satelites Sorted by Name

This page lists the planets and their satelites in alphabetical order. The abbreviations used are:

Name	Name of the planet or satelite.
Orbits	Sun or planet about which it orbits.
Vo	Objects magnitude in visible at opposition.
Distance	Distance to the Sun or to the planet center. Measured in 10^3 km.
O_Period	Orbital period in days.
Incl	Orbital inclination in degrees.
Eccen	Orbital Eccentricity.
Radius	Radius in km.
Mass	Mass in kg.
Density	Density in g/cm^3.

Name	Orbits	Vo	Distance	O_Period	Incl	Eccen	Radius	Mass	Density
Adrastea	Jupiter	18.7	128.98	0.298	0	0	12x8	?	?
Amalthea	Jupiter	14.1	181.30	0.498	0.4	0	135x75	?	?
Ananke	Jupiter	18.9	21,200	631	147	0.17	15	?	?
Ariel	Uranus	14.4	191.24	2.520	0.00	0.00	580	1.26e21	1.66
Atlas	Saturn	18.0	137.64	0.602	0	0	20x15	?	?
Belinda	Uranus	22	75.26	0.624	0.03	0	35	?	?
Bianca	Uranus	23	59.16	0.435	0.16	0	20	?	?
Callisto	Jupiter	5.6	1,883	16.689	0.28	0.01	2,400	1.08e23	1.86
Calypso	Saturn	19.0	294.66	1.888	0	0	15x10	?	?
Carme	Jupiter	17.9	22,600	692	163	0.21	22	?	?
Charon	Pluto	16.8	19.64	6.387	98.8	0.00	635	1.77e21	2.0
Cordelia	Uranus	24.0	49.750	0.335	0.14	0	15	?	?
Cressida	Uranus	22	61.77	0.464	0.04	0	35	?	?
Deimos	Mars	12.3	23.46	1.263	0.9-2.7	0.00	8x6	1.8e15	1.7
Desdemona	Uranus	22	62.66	0.474	0.16	0	30	?	?
Despina	Neptune	23	52.50	0.333	0	0	90	?	?
Dione	Saturn	10.4	377.40	2.737	0.02	0.00	560	1.05e21	1.44
Earth	Sun		149,600	365.256	0.000	0.0167	6,378	5.976e24	5.52
Elara	Jupiter	16.6	11,737	259.65	28	0.21	40	?	?
Enceladus	Saturn	11.7	238.02	1.370	0.02	0.00	250	8.4e19	1.24
Epimetheus	Saturn	15.7	151.422	0.694	0.34	0.01	70x50	?	?
Europa	Jupiter	5.3	670.90	3.551	0.47	0.01	1,569	4.8e22	2.97
Galatea	Neptune	23	62.00	0.429	0	0	75	?	?
Ganymede	Jupiter	4.6	1,070	7.155	0.19	0.00	2,631	1.48e23	1.94

Name	Orbits	Vo	Distance	O_Period	Incl	Eccen	Radius	Mass	Density
Helene	Saturn	18.4	377.40	2.737	0.2	0.01	18x15	?	?
Himalia	Jupiter	15.0	11,480	250.57	28	0.16	90	?	?
Hyperion	Saturn	14.2	1,481.0	21.277	0.43	0.10	175x100	?	?
Iapetus	Saturn	10.2-11.9	3,561.3	79.331	14.72	0.03	720	1.88e21	1.21
Io	Jupiter	5	421.60	1.769	0.04	0.00	1815	8.94e22	3.57
Janus	Saturn	14.5	151.472	0.695	0.14	0.01	110x80	?	?
Juliet	Uranus	22	64.36	0.493	0.06	0	40	?	?
Jupiter	Sun	-2.7	778,330	4,332.71	1.308	0.0483	71,492	1.9e27	1.33
Larissa	Neptune	21	73.60	0.554	0	0	95	?	?
Leda	Jupiter	20.2	11,094	238.72	27	0.15	8	?	?
Lysithea	Jupiter	18.2	11,720	259.22	29	0.11	20	?	?
Mars	Sun	-2.0	227,940	686.98	1.850	0.0934	3,393	6.421e23	3.95
Mercury	Sun	-1.9	57,910	87.969	7	0.2056	2,439	3.303e23	5.43
Metis	Jupiter	17.5	127.96	0.295	0	0.0	20	?	?
Mimas	Saturn	12.9	185.52	0.942	1.53	0.02	195	3.8e19	1.17
Miranda	Uranus	16.5	129.78	1.414	3.4	0.00	235	6.89e19	1.35
Moon	Earth	-12.7	384.4	27.322	18.3-28.6	0.05	1,738	7.349e22	3.34
Naiad	Neptune	25	48.00	0.296	0	0	25	?	?
Neptune	Sun	7.8	4,497,070	60,190	1.774	0.0097	24,764	1.024e26	1.64
Nereid	Neptune	18.7	5,513.40	360.16	29	0.75	170	?	?
Oberon	Uranus	14.2	582.60	13.463	0.00	0.00	760	3.03e21	1.58
Ophelia	Uranus	24	53.76	0.376	0.09	0.01	15	?	?
Pan	Saturn		133	0.58	?	?	9.655	?	?
Pandora	Saturn	16.5	141.70	0.629	0	0.00	55x35	?	?

Name	Orbits	Vo	Distance	O_Period	Incl	Eccen	Radius	Mass	Density
Pasiphae	Jupiter	16.9	23,500	735	147	0.38	35	?	?

Phobos	Mars	11.3	9.380	0.319	1.0	0.01	14x10	1.08e16	2.0
Phoebe	Saturn	16.5	12,952	550.48	175.3	0.16	110	?	?
Pluto	Sun	15.1	5,913,520	90,800	17.148	0.2482	1,160	1.29e22	2.03
Proteus	Neptune	20	117.60	1.121	0	0	200	?	?
Portia	Uranus	21	66.10	0.513	0.09	0	55	?	?
Prometheus	Saturn	15.8	139.35	0.613	0	0.00	70x40	?	?
Puck	Uranus	20	86.01	0.762	0.31	0	75	?	?
Rhea	Saturn	9.7	527.04	4.518	0.35	0.00	765	2.49e21	1.33
Rosalind	Uranus	22	69.93	0.558	0.28	0	30	?	?
Saturn	Sun	0.7	1,426,980	10,759.5	2.488	0.0560	60,268	5.688e26	0.69
Sinope	Jupiter	18.0	23,700	758	153	0.28	20	?	?
Sun	---	---	---	---	---	---	695,000	1.989e30	---
Telesto	Saturn	18.7	294.66	1.888	0	0	12	?	?
Tethys	Saturn	10.2	294.66	1.888	1.09	0.00	525	7.55e20	1.26
Thalassa	Neptune	24	50.00	0.312	4.5	0	40	?	?
Thebe	Jupiter	16.0	221.90	0.675	0.8	0.01	50	?	?
Titan	Saturn	8.3	1,221.85	15.945	0.33	0.03	2,575	1.35e23	1.88
Titania	Uranus	14.0	435.84	8.706	0.00	0.00	790	3.48e21	1.68
Triton	Neptune	13.6	354.80	5.877	157	0.00	1,350	2.14e22	2.07
Umbriel	Uranus	15.3	265.97	4.144	0.00	0.00	585	1.33e21	1.51
Uranus	Sun	5.5	2,870,990	30,685	0.774	0.0461	25,559	8.684e25	1.29
Venus	Sun	-4.4	108,200	224.701	3.394	0.0068	6,051	4.870e24	5.25

Solar System Home

Planets & Satelites Sorted by Radius

This page lists the planets and their satelites by their radius. The abbreviations used are:

```
Name            Name of the planet or satelite.
Orbits          Sun or planet about which it orbits.
Vo              Objects magnitude in visible at opposition.
Distance        Distance to the Sun or to the planet center.
                Measured in 10^3 km.
O_Period        Orbital period in days.
Incl            Orbital inclination in degrees.
Eccen           Orbital Eccentricity.
Radius          Radius in km.
Mass            Mass in kg.
Density         Density in g/cm^3.
```

Name	Orbits	Vo	Distance	O_Period	Incl	Eccen	Radius	Mass	Density
Deimos	Mars	12.3	23.46	1.263	0.9-2.7	0.00	8x6	1.8e15	1.7
Leda	Jupiter	20.2	11,094	238.72	27	0.15	8	?	?
Pan	Saturn		133	0.58	?	?	9.655	?	?
Adrastea	Jupiter	18.7	128.98	0.298	0	0	12x8	?	?
Telesto	Saturn	18.7	294.66	1.888	0	0	12	?	?
Phobos	Mars	11.3	9.380	0.319	1.0	0.01	14x10	1.08e16	2.0
Calypso	Saturn	19.0	294.66	1.888	0	0	15x10	?	?
Ananke	Jupiter	18.9	21,200	631	147	0.17	15	?	?
Cordelia	Uranus	24.0	49.750	0.335	0.14	0	15	?	?
Ophelia	Uranus	24	53.76	0.376	0.09	0.01	15	?	?
Helene	Saturn	18.4	377.40	2.737	0.2	0.01	18x15	?	?
Atlas	Saturn	18.0	137.64	0.602	0	0	20x15	?	?
Bianca	Uranus	23	59.16	0.435	0.16	0	20	?	?
Lysithea	Jupiter	18.2	11,720	259.22	29	0.11	20	?	?
Metis	Jupiter	17.5	127.96	0.295	0	0.0	20	?	?
Sinope	Jupiter	18.0	23,700	758	153	0.28	20	?	?
Carme	Jupiter	17.9	22,600	692	163	0.21	22	?	?
Naiad	Neptune	25	48.00	0.296	0	0	25	?	?
Desdemona	Uranus	22	62.66	0.474	0.16	0	30	?	?
Rosalind	Uranus	22	69.93	0.558	0.28	0	30	?	?
Belinda	Uranus	22	75.26	0.624	0.03	0	35	?	?
Cressida	Uranus	22	61.77	0.464	0.04	0	35	?	?
Pasiphae	Jupiter	16.9	23,500	735	147	0.38	35	?	?
Thalassa	Neptune	24	50.00	0.312	4.5	0	40	?	?

Name	Orbits	Vo	Distance	O_Period	Incl	Eccen	Radius	Mass	Density
Elara	Jupiter	16.6	11,737	259.65	28	0.21	40	?	?
Juliet	Uranus	22	64.36	0.493	0.06	0	40	?	?
Thebe	Jupiter	16.0	221.90	0.675	0.8	0.01	50	?	?
Pandora	Saturn	16.5	141.70	0.629	0	0.00	55x35	?	?
Portia	Uranus	21	66.10	0.513	0.09	0	55	?	?
Prometheus	Saturn	15.8	139.35	0.613	0	0.00	70x40	?	?
Epimetheus	Saturn	15.7	151.422	0.694	0.34	0.01	70x50	?	?
Galatea	Neptune	23	62.00	0.429	0	0	75	?	?
Puck	Uranus	20	86.01	0.762	0.31	0	75	?	?
Despina	Neptune	23	52.50	0.333	0	0	90	?	?
Himalia	Jupiter	15.0	11,480	250.57	28	0.16	90	?	?
Larissa	Neptune	21	73.60	0.554	0	0	95	?	?
Janus	Saturn	14.5	151.472	0.695	0.14	0.01	110x80	?	?
Phoebe	Saturn	16.5	12,952	550.48	175.3	0.16	110	?	?
Amalthea	Jupiter	14.1	181.30	0.498	0.4	0	135x75	?	?
Nereid	Neptune	18.7	5,513.40	360.16	29	0.75	170	?	?
Hyperion	Saturn	14.2	1,481.0	21.277	0.43	0.10	175x100	?	?
Mimas	Saturn	12.9	185.52	0.942	1.53	0.02	195	3.8e19	1.17
Proteus	Neptune	20	117.60	1.121	0	0	200	?	?
Miranda	Uranus	16.5	129.78	1.414	3.4	0.00	235	6.89e19	1.35
Enceladus	Saturn	11.7	238.02	1.370	0.02	0.00	250	8.4e19	1.24
Tethys	Saturn	10.2	294.66	1.888	1.09	0.00	525	7.55e20	1.26
Dione	Saturn	10.4	377.40	2.737	0.02	0.00	560	1.05e21	1.44
Ariel	Uranus	14.4	191.24	2.520	0.00	0.00	580	1.26e21	1.66

Name	Orbits	Vo	Distance	O_Period	Incl	Eccen	Radius	Mass	Density
Umbriel	Uranus	15.3	265.97	4.144	0.00	0.00	585	1.33e21	1.51

Charon	Pluto	16.8	19.64	6.387	98.8	0.00	635	1.77e21	2.0
Iapetus	Saturn	10.2-11.9	3,561.3	79.331	14.72	0.03	720	1.88e21	1.21
Oberon	Uranus	14.2	582.60	13.463	0.00	0.00	760	3.03e21	1.58
Rhea	Saturn	9.7	527.04	4.518	0.35	0.00	765	2.49e21	1.33
Titania	Uranus	14.0	435.84	8.706	0.00	0.00	790	3.48e21	1.68
Pluto	Sun	15.1	5,913,520	90,800	17.148	0.2482	1,160	1.29e22	2.03
Triton	Neptune	13.6	354.80	5.877	157	0.00	1,350	2.14e22	2.07
Europa	Jupiter	5.3	670.90	3.551	0.47	0.01	1,569	4.8e22	2.97
Moon	Earth	-12.7	384.4	27.322	18.3-28.6	0.05	1,738	7.349e22	3.34
Io	Jupiter	5	421.60	1.769	0.04	0.00	1,815	8.94e22	3.57
Callisto	Jupiter	5.6	1,883	16.689	0.28	0.01	2,400	1.08e23	1.86
Mercury	Sun	-1.9	57,910	87.969	7	0.2056	2,439	3.303e23	5.43
Titan	Saturn	8.3	1,221.85	15.945	0.33	0.03	2,575	1.35e23	1.88
Ganymede	Jupiter	4.6	1,070	7.155	0.19	0.00	2,631	1.48e23	1.94
Mars	Sun	-2.0	227,940	686.98	1.850	0.0934	3,393	6.421e23	3.95
Venus	Sun	-4.4	108,200	224.701	3.394	0.0068	6,051	4.870e24	5.25
Earth	Sun		149,600	365.256	0.000	0.0167	6,378	5.976e24	5.52
Neptune	Sun	7.8	4,497,070	60,190	1.774	0.0097	24,764	1.024e26	1.64
Uranus	Sun	5.5	2,870,990	30,685	0.774	0.0461	25,559	8.684e25	1.29
Saturn	Sun	0.7	1,426,980	10,759.5	2.488	0.0560	60,268	5.688e26	0.69
Jupiter	Sun	-2.7	778,330	4,332.71	1.308	0.0483	71,492	1.9e27	1.33
Sun	---	---	---	---	---	---	695,000	1.989e30	---

Solar System Home

Planets & Satelites Sorted by Distance

This page lists the planets and their satelites by their distance from the Sun or planet. The abbreviations used are:

Name	Name of the planet or satelite.
Orbits	Sun or planet about which it orbits.
Vo	Objects magnitude in visible at opposition.
Distance	Distance to the Sun or to the planet center. Measured in 10^3 km.
O_Period	Orbital period in days.
Incl	Orbital inclination in degrees.
Eccen	Orbital Eccentricity.
Radius	Radius in km.
Mass	Mass in kg.
Density	Density in g/cm^3.

Name	Orbits	Vo	Distance	O_Period	Incl	Eccen	Radius	Mass	Density
Sun	---	---	---	---	---	---	695,000	1.989e30	---
Phobos	Mars	11.3	9.380	0.319	1.0	0.01	14x10	1.08e16	2.0
Charon	Pluto	16.8	19.64	6.387	98.8	0.00	635	1.77e21	2.0
Deimos	Mars	12.3	23.46	1.263	0.9-2.7	0.00	8x6	1.8e15	1.7
Naiad	Neptune	25	48.00	0.296	0	0	25	?	?
Cordelia	Uranus	24.0	49.750	0.335	0.14	0	15	?	?
Thalassa	Neptune	24	50.00	0.312	4.5	0	40	?	?
Despina	Neptune	23	52.50	0.333	0	0	90	?	?
Ophelia	Uranus	24	53.76	0.376	0.09	0.01	15	?	?
Bianca	Uranus	23	59.16	0.435	0.16	0	20	?	?
Cressida	Uranus	22	61.77	0.464	0.04	0	35	?	?
Galatea	Neptune	23	62.00	0.429	0	0	75	?	?
Desdemona	Uranus	22	62.66	0.474	0.16	0	30	?	?
Juliet	Uranus	22	64.36	0.493	0.06	0	40	?	?
Portia	Uranus	21	66.10	0.513	0.09	0	55	?	?
Rosalind	Uranus	22	69.93	0.558	0.28	0	30	?	?
Larissa	Neptune	21	73.60	0.554	0	0	95	?	?
Belinda	Uranus	22	75.26	0.624	0.03	0	35	?	?
Puck	Uranus	20	86.01	0.762	0.31	0	75	?	?
Proteus	Neptune	20	117.60	1.121	0	0	200	?	?
Metis	Jupiter	17.5	127.96	0.295	0	0.0	20	?	?
Adrastea	Jupiter	18.7	128.98	0.298	0	0	12x8	?	?
Miranda	Uranus	16.5	129.78	1.414	3.4	0.00	235	6.89e19	1.35
Pan	Saturn		133	0.58	?	?	9.655	?	?

Name	Orbits	Vo	Distance	O_Period	Incl	Eccen	Radius	Mass	Density
Atlas	Saturn	18.0	137.64	0.602	0	0	20x15	?	?
Prometheus	Saturn	15.8	139.35	0.613	0	0.00	70x40	?	?
Pandora	Saturn	16.5	141.70	0.629	0	0.00	55x35	?	?
Epimetheus	Saturn	15.7	151.422	0.694	0.34	0.01	70x50	?	?
Janus	Saturn	14.5	151.472	0.695	0.14	0.01	110x80	?	?
Amalthea	Jupiter	14.1	181.30	0.498	0.4	0	135x75	?	?
Mimas	Saturn	12.9	185.52	0.942	1.53	0.02	195	3.8e19	1.17
Ariel	Uranus	14.4	191.24	2.520	0.00	0.00	580	1.26e21	1.66
Thebe	Jupiter	16.0	221.90	0.675	0.8	0.01	50	?	?
Enceladus	Saturn	11.7	238.02	1.370	0.02	0.00	250	8.4e19	1.24
Umbriel	Uranus	15.3	265.97	4.144	0.00	0.00	585	1.33e21	1.51
Calypso	Saturn	19.0	294.66	1.888	0	0	15x10	?	?
Telesto	Saturn	18.7	294.66	1.888	0	0	12	?	?
Tethys	Saturn	10.2	294.66	1.888	1.09	0.00	525	7.55e20	1.26
Triton	Neptune	13.6	354.80	5.877	157	0.00	1,350	2.14e22	2.07
Dione	Saturn	10.4	377.40	2.737	0.02	0.00	560	1.05e21	1.44
Helene	Saturn	18.4	377.40	2.737	0.2	0.01	18x15	?	?
Moon	Earth	-12.7	384.4	27.322	18.3-28.6	0.05	1,738	7.349e22	3.34
Io	Jupiter	5	421.60	1.769	0.04	0.00	1815	8.94e22	3.57
Titania	Uranus	14.0	435.84	8.706	0.00	0.00	790	3.48e21	1.68
Rhea	Saturn	9.7	527.04	4.518	0.35	0.00	765	2.49e21	1.33
Oberon	Uranus	14.2	582.60	13.463	0.00	0.00	760	3.03e21	1.58
Europa	Jupiter	5.3	670.90	3.551	0.47	0.01	1,569	4.8e22	2.97
Ganymede	Jupiter	4.6	1,070	7.155	0.19	0.00	2,631	1.48e23	1.94

Name	Orbits	Vo	Distance	O_Period	Incl	Eccen	Radius	Mass	Density

Titan	Saturn	8.3	1,221.85	15.945	0.33	0.03	2,575	1.35e23	1.88
Hyperion	Saturn	14.2	1,481.0	21.277	0.43	0.10	175x100	?	?
Callisto	Jupiter	5.6	1,883	16.689	0.28	0.01	2,400	1.08e23	1.86
Iapetus	Saturn	10.2-11.9	3,561.3	79.331	14.72	0.03	720	1.88e21	1.21
Nereid	Neptune	18.7	5,513.40	360.16	29	0.75	170	?	?
Leda	Jupiter	20.2	11,094	238.72	27	0.15	8	?	?
Himalia	Jupiter	15.0	11,480	250.57	28	0.16	90	?	?
Lysithea	Jupiter	18.2	11,720	259.22	29	0.11	20	?	?
Elara	Jupiter	16.6	11,737	259.65	28	0.21	40	?	?
Phoebe	Saturn	16.5	12,952	550.48	175.3	0.16	110	?	?
Ananke	Jupiter	18.9	21,200	631	147	0.17	15	?	?
Carme	Jupiter	17.9	22,600	692	163	0.21	22	?	?
Pasiphae	Jupiter	16.9	23,500	735	147	0.38	35	?	?
Sinope	Jupiter	18.0	23,700	758	153	0.28	20	?	?
Mercury	Sun	-1.9	57,910	87.969	7	0.2056	2,439	3.303e23	5.43
Venus	Sun	-4.4	108,200	224.701	3.394	0.0068	6,051	4.870e24	5.25
Earth	Sun		149,600	365.256	0.000	0.0167	6,378	5.976e24	5.52
Mars	Sun	-2.0	227,940	686.98	1.850	0.0934	3,393	6.421e23	3.95
Jupiter	Sun	-2.7	778,330	4,332.71	1.308	0.0483	71,492	1.9e27	1.33
Saturn	Sun	0.7	1,426,980	10,759.5	2.488	0.0560	60,268	5.688e26	0.69
Uranus	Sun	5.5	2,870,990	30,685	0.774	0.0461	25,559	8.684e25	1.29
Neptune	Sun	7.8	4,497,070	60,190	1.774	0.0097	24,764	1.024e26	1.64
Pluto	Sun	15.1	5,913,520	90,800	17.148	0.2482	1,160	1.29e22	2.03

Terms and Definitions

A

accretion
accumulation of dust and gas into larger bodies

albedo
reflectivity of an object; ratio of reflected light to incident light

albedo feature
a dark or light marking on the surface of an object that may not be a geological or topographical feature

antipodal point
the point that is directly on the opposite side of the planet

aphelion
the point in its orbit where a planet is farthest from the Sun

asteroid number
asteroids are assigned a serial number when they are discovered; it has no particular meaning except that asteroid N+1 was discovered after asteroid N

astronomical unit (AU)
the average distance from the Earth to the Sun; 1AU is 149,597,870 km

atmosphere
1 atmosphere is 14.7 pounds per square inch; standard atmospheric pressure at sea level on Earth

aurora
a glow in a planets ionosphere caused by the interaction between the planet's magnetic field and charged particles from the Sun

aurora borealis
the *Northern Lights* caused by the interaction between the solar wind, the Earth's magnetic field and the upper atmosphere; a similar effect happens in the southern hemisphere where it is known as the aurora austrailis

B

bar
1 bar is equivalent to 0.987 atmosphere or 10000 newtons per square meter

C

calcium K

a narrow wavelength of blue light which is emitted and absorbed by ions of the element calcium

caldera

crater formed by an explosion or collapse of a volcanic vent

carbonate

a compound containing carbon and oxygen (ie calcium carbonate aka limestone)

catena

a chain of craters

cavus

hollows, irregular depressions

chaos

distinctive area of broken terrain

chasma

a canyon

chromosphere

the lower level of the solar atmosphere between the photosphere and the corona

colles

a small hill or knob

coma

the dust and gas surrounding an active comet's nucleus

convection

fluid circulation driven by large temperature gradients; the transfer of heat by this automatic circulation

corona

The upper level of the solar atmosphere

corona

an ovoid–shaped feature

coronagraph

a special telescope which blocks light from the disk of the Sun in order to study the faint solar atmosphere

crater

depression formed by the impact of a meteorite; depression around the orifice of a volcano

D

density

measured in grams per cubic centimeter (or kilograms per liter); the density of water is 1.0; iron is 7.9; lead is 11.3

dorsum

a ridge

E

eccentricity
: the eccentricity of an ellipse (planetary orbit) is the ratio of the distance between the focii and the major axis

F

facula
: a bright spot

filament
: a strand of cool gas in the solar corona, which appears dark as seen against the disk of the Sun

flexus
: cuspate linear feature

fluctus
: flow terrain

fossa
: a long, narrow, shallow depression

G

granulation
: a pattern of small cells seen on the surface of the Sun caused by the convective motions of the hot solar gas

greenhouse effect
: increase in temperature caused when incoming solar radiation is passed but outgoing thermal radiation is blocked by the atmosphere (carbon dioxide is the major factor)

H

h–alpha
: a narrow wavelength of red light which is emitted and absorbed by the element hydrogen; this wavelength is often used to study the Sun

hemisphere
: a half of the celestial sphere divided into two halves by the horizon, the celestial equator, or the ecliptic

I

ice

used by planetary scientists to refer to water, methane, and ammonia which usually occur as solids in the outer solar system

ionosphere

a region of charged particales in a planet's upper atmosphere; the part of the earth's atmosphere beginning at an altitude of about 25 miles and extending outward 250 miles or more

J

K

Kelvin (°K)

0° K is absolute zero; water melts at 273° K (0° C, 32° F); water boils at 373° K (100° C, 212° F)

kilogram (kg)

1 kilogram is equivalent to 1000 grams or 2.2 pounds; the mass of a liter of water

kilometer (km)

1 kilometer is equivalent to 1000 meters or 0.62 miles

L

labes

a Landslide

labyrinthus

an intersecting valley complex

lacus

a lake

light–year

1 light–year is equivalent to 9.46053e12 km, 5,880,000,000,000 miles or 206,264 AU; the distance traveled by light in a year

limb

the outer edge of the apparent disk of a celestial body

linea

an elongate marking

M

macula

a dark spot

magnetograph

a special telescope which analyzes the color and polarization of sunlight in order to measure the magnetic field of the Sun

magnetosphere

the region of space in which a planet's magnetic field dominates that of the solar wind

magnetotail

the portion of a planetary magnetosphere which is pushed in the direction of the solar wind

mare

a sea

mensa

mesa, flat–topped elevation

millibar

1/1000 of a bar; standard sea–level pressure is about 1013 millibars

mons

a mountain

N

neutrino

a fundamental particle supposedly produced in massive numbers by the nuclear reactions in stars; they are very hard to detect since the vast majority of them pass completely through the Earth without interacting

nuclear fusion

a nuclear process whereby several small nuclei are combined to make a larger one whose mass is slightly smaller than the sum of the small ones; the difference in mass is converted to energy by Einstein's famous equivalence E=mc^2; this is the source of the Sun's energy therefore ultimately of (almost) all energy on Earth

O

oceanus

an ocean

ovoid

shaped like an egg

P

palus

a swamp

patera

shallow crater; scalloped, complex edge

penumbra

the outer filamentary region of a sunspot

perihelion

the point in its orbit where a planet is closest to the Sun

perturb

to cause a planet or satellite to deviate from a theoretically regular orbital motion

photosphere

the visible surface of the Sun

plage

bright regions seen in the solar chromosphere

planitia

low plain

planum

plateau or high plain

polarization

a special property of light; light has three properties, brightness, color and polarization

prominence

a strand of cool gas in the solar corona which appears bright when seen at the edge of the Sun against the blackness of space

promontorium

a cape

Q

R

red giant

a star that has low surface temperature and a diameter that is large relative to the Sun

regio

region

regolith

the layer of rocky debris and dust made by metoritic impact that forms the uppermost surface of planets, satellites and asteroids

resolution

the amount of small detail visible in an image; low resolution shows only large features, high resolution shows many small details

retrograde

rotation or orbital motion in a clockwise direction when viewed from the north pole of the ecliptic (or of the rotating object)

rift valley

an elongated valley formed by the depression of a block of the planet's crust between two faults or groups of faults of approximately parallel strike

rima

fissure

Roche limit

the closest a fluid body can orbit to its parent planet without being pulled apart by tidal forces

rupes

a scarp

S

scarp

a line of cliffs produced by faulting or erosion

scopulus

lobate or irregular scarp

semimajor axis

one–half of the longest dimension of an ellipse

shepherd satellite

a satellite which constrains the extent of a planetary ring through gravitational forces

silicate

a rock or mineral whose structure is dominated by bonds of silicon and oxygen atoms (ie. olivine)

sinus

a bay

solar wind

the high–speed outflow of energetic charged particles and entrained magnetic field lines for the solar corona

spicules

grass–like patterns of gas seen in the solar atmosphere

sublime

to change directly from a solid to a gas without becoming liquid

sulcus

subparallel furrows and ridges

sulfuric acid

a heavy corrosive oily dibasic strong acid H2SO4 that is colorless when pure and is a vigorous oxidizing and dehydrating agent

T

tectonic

deformation forces acting on a planet's crust

terminator

the dividing line between the illuminated and the unilluminated part of the moon's or a planet's disk

terra

extensive land mass

tessera

tile; polygonal ground

tholus

small domical mountain or hill

tidal heating

frictional heating of a satellite's interior due to flexure caused by the gravitational pull of its parent planet and possibly neighboring satellites

U

umbra

the dark central region of a sunspot

undae

dunes

V

vallis

sinuous valley

volatile

compounds with low melting temperatures, such as hydrogen, helium, water, ammonia, carbon dioxide and methane

vastitas

widespread lowlands

W

white dwarf

a whitish star of high surface temperature and low intrinsic brightness with a mass approximately equal to that of the Sun but with a density many times larger

X

Y

Z

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Background Material for Science Teachers JULY 1994 -- Periodic Comet Shoemaker–Levy 9 Collides with Jupiter

Comet Shoemaker–Levy 9 is expected to collide with Jupiter in July 1994. From this historic event, scientists hope to learn more about comets, Jupiter, and the physics of high velocity planetary impacts.

Hypertext version by Calvin J. Hamilton

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Introduction

For a period of about six days centered on July 19, 1994, fragments of Comet Shoemaker–Levy 9 are expected to collide with Jupiter, the solar system's largest planet. No such event has ever before been available for study. The energy released by the larger fragments during impact will be more than 10,000 times the energy released by a 100–megaton hydrogen bomb! Unfortunately for observers, the collisions will occur on the night side of Jupiter, which also will be the back side as seen from Earth. The collisions can still be studied in many ways, nevertheless, by spacecraft more advantageously located, by light of the collisions reflected from Jupiter's satellites, and by the effects of the impacts upon the Jovian atmosphere. (The impact sites will rotate into view from Earth about 20 minutes after each collision.)

Stupendous as these collisions will be, they will occur on the far side of a body half a billion miles from Earth. There will be no display visible to the general public, not even a display as obvious as a faint terrestrial meteor. Amateur astronomers may note a few seconds of brightening of the inner satellites of Jupiter during the impacts, and they might observe minor changes in the Jovian cloud structure during the days following the impacts. The real value of this most unusual event will come from scientific studies of the comet's composition, of the impact phenomena themselves, and of the response of a planetary atmosphere and magnetosphere to such a series of insults.

This booklet offers some background material on Jupiter, comets, what has and possibly will happen, and how scientists propose to take advantage of the impact events.

Table of Contents Section 1

1. What is a Comet?

Comets are small, fragile, irregularly shaped bodies composed of a mixture of non–volatile grains and frozen gases. They usually follow highly elongated paths around the Sun. Most become visible, even in telescopes, only when they get near enough to the Sun for the Sun's radiation to start subliming the volatile gases, which in turn blow away small bits of the solid material. These materials expand into an enormous escaping atmosphere called the coma, which becomes far bigger than a planet, and they are forced back into long tails of dust and gas by radiation and charged particles flowing from the Sun. Comets are cold bodies, and we see them only because the gases in their comae and tails fluoresce in sunlight (somewhat akin to a fluorescent light) and because of sunlight reflected from the solids. Comets are regular members of the solar system family, gravitationally bound to the Sun. They are generally believed to be made of material, originally in the outer part of the solar system, that didn't get incorporated into the planets — leftover debris, if you will. It is the very fact that they are thought to be composed of such unchanged primitive material that makes them extremely interesting to scientists who wish to learn about conditions during the earliest period of the solar system.

Comets are very small in size relative to planets. Their average diameters usually range from 750 m or less to about 20 km. Recently, evidence has been found for much larger distant comets, perhaps having diameters of 300 km or more, but these sizes are still small compared to planets. Planets are usually more or less spherical in shape, usually bulging slightly at the equator. Comets are irregular in shape, with their longest dimension often twice the shortest. (See Appendix A, Table 3.) The best evidence suggests that comets are very fragile. Their tensile strength (the stress they can take without being pulled apart) appears to be only about 1,000 dynes/cm^2 (about 2 lb./ft.^2). You could take a big piece of cometary material and simply pull it in two with your bare hands, something like a poorly compacted snowball.

Comets, of course, must obey the same universal laws of motion as do all other bodies. Where the orbits of planets around the Sun are nearly circular, however, the orbits of comets are quite elongated. Nearly 100 known comets have periods (the time it takes them to make one complete trip around the Sun) five to seven Earth years in length. Their farthest point from the Sun (their aphelion) is near Jupiter's orbit, with the closest point (perihelion) being much nearer to Earth. A few comets like Halley have their aphelions beyond Neptune (which is six times as far from the Sun as Jupiter). Other comets come from much farther out yet, and it may take them thousands or even hundreds of thousands of years to make one complete orbit around the Sun. In all cases, if a comet approaches near to Jupiter, it is strongly attracted by the gravitational pull of that giant among planets, and its orbit is perturbed (changed), sometimes radically. This is part of what happened to Shoemaker–Levy 9. (See Sections 2 and 4 for more details.)

The nucleus of a comet, which is its solid, persisting part, has been called an icy conglomerate, a dirty snowball, and other colorful but even less accurate descriptions. Certainly a comet nucleus contains silicates akin to some ordinary Earth rocks in composition, probably mostly in very small grains and pieces. Perhaps the grains are glued together into larger pieces by the frozen gases. A nucleus appears to include complex carbon compounds and perhaps some free carbon, which make it very black in color. Most notably, at least when young, it contains many frozen gases, the most common being ordinary water. In the low pressure conditions of space, water sublimes, that is, it goes directly from solid to gas — just like dry ice does on Earth. Water probably makes up 75–80% of the volatile material in most comets. Other common ices are carbon monoxide (CO), carbon dioxide (CO2), methane (CH4), ammonia (NH3), and formaldehyde (H2CO). Volatiles and solids appear to be fairly well mixed throughout the nucleus of a new comet approaching the Sun for the first time. As a comet ages from many trips close to the Sun, there is evidence that it loses most of its ices, or at least those ices anywhere near the nucleus surface, and becomes just a very fragile old rock in appearance, indistinguishable at a distance from an asteroid.

A comet nucleus is small, so its gravitational pull is very weak. You could run and jump completely off of it (if you could get traction). The escape velocity is only about 1 m/s (compared to 11 km/s on Earth). As a result, the escaping gases and the small solid particles (dust) that they drag with them never fall back to the nucleus surface. Radiation pressure, the pressure of sunlight, forces the dust particles back into a dust tail in the direction opposite to the Sun. A comet's tail can be tens of millions of kilometers in length when seen in the reflected sunlight. The gas molecules are torn apart by solar ultraviolet light, often losing electrons and becoming electrically charged fragments or ions. The ions interact with the wind of charged particles flowing out from the Sun and are forced back into an ion tail, which again can extend for millions of kilometers in the direction opposite to the Sun. These ions can be seen as they fluoresce in sunlight.

Every comet then really has two tails, a dust tail and an ion tail. If the comet is faint, only one or neither tail may be detectable, and the comet may appear just as a fuzzy blob of light, even in a big telescope. The density of material in the coma and tails is very low, lower than the best vacuum that can be produced in most laboratories. In 1986 the Giotto spacecraft flew right through Comet Halley only a few hundred kilometers from the nucleus. Though the coma and tails of a comet may extend for tens of millions of kilometers and become easily visible to the naked eye in Earth's night sky, as Comet West's were in 1976, the entire phenomenon is the product of a tiny nucleus only a few kilometers across.

Because comet nuclei are so small, they are quite difficult to study from Earth. They always appear at most as a point of light in even the largest telescope, if not lost completely in the glare of the coma. A great deal was learned when the European Space Agency, the Soviet Union, and the Japanese sent spacecraft to fly by Comet Halley in 1986. For the first time, actual images of an active nucleus were obtained (see Figure 1) and the composition of the dust and gases flowing from it was directly measured. Early in the next century the Europeans plan to send a spacecraft called Rosetta to rendezvous with a comet and watch it closely for a long period of time. Even this sophisticated mission is not likely to tell scientists a great deal about the interior structure of comets, however. Therefore, the opportunity to reconstruct the events that occurred when Shoemaker–Levy 9 split and to study those that will occur when the fragments are destroyed in Jupiter's atmosphere is uniquely important (see Sections 4, 7, and 8).

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2. The Motion of Comets

Comets necessarily obey the same physical laws as every other object. They move according to the basic laws of motion and of universal gravitation discovered by Newton in the 17th century (ignoring very small relativistic corrections). If one considers only two bodies –– either the Sun and a planet, or the Sun and a comet –– the smaller body appears to follow an elliptical path or orbit about the Sun, which is at one focus of the ellipse. The geometrical constants which fully define the shape of the ellipse are the semimajor axis a and the eccentricity e (see Figure 2). The semiminor axis b is related to those two quantities by the equation b = a(1–e^2). The focus is located a distance ae from the center of the ellipse. Three further constants are required if one wishes to describe the orientation of the ellipse in space relative to some coordinate system, and a fourth quantity is required if one wishes to define the location of a body in that elliptical orbit.

In Figure 2B several ellipses are drawn, all having the same semimajor axis but different eccentricities. Eccentricity is a mathematical measure of departure from circularity. A circle has zero eccentricity, and most of the planets have orbits which are nearly circles. Only Pluto and Mercury have eccentricities exceeding 0.1. Comets, however, have very large eccentricities, often approaching one, the value for a parabola. Such highly eccentric orbits are just as possible as circular orbits, as far as the laws of motion are concerned.

The solar system consists of the Sun, nine planets, numerous satellites and asteroids, comets, and various small debris. At any given time the motion of any solar system body is affected by the gravitational pulls of all of the others. The Sun's pull is the largest by far, unless one body approaches very closely to another, so orbit calculations usually are carried out as two–body calculations (the body in question and the Sun) with small perturbations (small added effects due to the pull of other bodies). In 1705 Halley noted in his original paper predicting the return of *his* comet that Jupiter undoubtedly had serious effects on the comet's motion, and he presumed Jupiter to be the cause of changes in the period (the time required for one complete revolution about the Sun) of the comet. (Comet Halley's period is usually stated to be 76 years, but in fact it has varied between 74.4 and 79.2 years during the past 2,000 years.) In that same paper Halley also became the first to note the very real possibility of the collision of comets with planets, but stated that he would leave the consequences of such a contact or shock to be discussed by the *Studious of Physical Matters.*

In the case of Shoemaker–Levy 9 we have the perfect example both of large perturbations and their possible consequences. The comet was fragmented and perturbed into an orbit where the pieces will hit Jupiter one period later. In general one must note that Jupiter's gravity (or that of other planets) is perfectly capable of changing the energy of a comet's orbit sufficiently to throw it clear out of the solar system (to give it escape velocity from the solar system) and has done so on numerous occasions. See Figure 3. This is exactly the same physical effect that permits using planets to change the orbital energy of a spacecraft in so–called *gravity–assist maneuvers* such as were used by the Voyager spacecraft to visit all the outer planets except Pluto.

One of Newton's laws of motion states that for every action there is an equal and opposite reaction. Comets expel dust and gas, usually from localized regions, on the sunward side of the nucleus. This action causes a reaction by the cometary nucleus, slightly speeding it up or slowing it down. Such effects are called *non–gravitational forces* and are simply rocket effects, as if someone had set up one or more rocket motors on the nucleus. In general both the size and shape of a comet's orbit are changed by the non–gravitational forces –– not by much but by enough to totally confound all of the celestial mechanics experts of the 19th and early 20th centuries. Comet Halley arrived at its point closest to the Sun (perihelion) in 1910 more than three days late, according to the best predictions. Only after F. L. Whipple published his icy conglomerate model of a degassing nucleus in 1950 did it all begin to make sense. The predictions for the time of perihelion passage of Comet Halley in 1986, which took into account a crude model for the reaction forces, were off by less than five hours.

Much of modern physics is expressed in terms of conservation laws, laws about quantities which do not change for a given system. Conservation of energy is one of these laws, and it says that energy may change form, but it cannot be created or destroyed. Thus the energy of motion (kinetic energy) of Shoemaker–Levy 9 will be changed largely to thermal energy when the comet is halted by Jupiter's atmosphere and destroyed in the process. When one body moves about another in the vacuum of space, the total energy (kinetic energy plus potential energy) is conserved.

Another quantity that is conserved is called angular momentum. In the first paragraph of this section, it was stated that the geometric constants of an ellipse are its semimajor axis and eccentricity. The dynamical constants of a body moving about another are energy and angular momentum. The total (binding) energy is inversely proportional to the semimajor axis. If the energy goes to zero, the semimajor axis becomes infinite and the body escapes. The angular momentum is proportional both to the eccentricity and the energy in a more complicated way, but, for a given energy, the larger the angular momentum the more elongated the orbit.

The laws of motion do not require that bodies move in circles (or even ellipses for that matter), but if they have some binding energy, they must move in ellipses (not counting perturbations by other bodies), and it is then the angular momentum which determines how elongated is the ellipse. Comets simply are bodies which in general have more angular momentum per unit mass than do planets and therefore move in more elongated orbits. Sometimes the orbits are so elongated that, because we can observe only a small part of them, they cannot be distinguished from a parabola, which is an orbit with an eccentricity of exactly one. In very general terms, one can say that the energy determines the size of the orbit and the angular momentum the shape.

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3. The Fragmentation of Comets

Every body is held together by two forces, its self– gravitation and its internal strength due to molecular bonding. With no external forces on it (and no initial rotation) a liquid body would form a perfect sphere just from self–gravitation (and from very weak molecular forces –– surface tension). Approaching another body, the sphere would begin to elongate toward that body. Finally, when the difference in gravitational force on the near side and far side of the former sphere exceeded the self– gravitation, the body would be torn apart. The distance from the larger body at which this disruption occurs is the so–called Roche limit, named for the man who first studied the problem. The differential gravitational effects of the Moon and the Sun are what raise the tides in Earth's oceans, and such forces are often referred to as tidal forces.

Solid bodies have intrinsic strength due to their molecular bonds. Aluminum wire may have a tensile strength of 2.4 x 10^9 dynes/cm^2 (5 million lb./ft.^2) and good steel wire a tensile strength 10 times larger still, which far exceeds the tidal force of anything short of a black hole. As stated in Section 1, comets have very low tensile strength, near 1 x 10^3 dynes/cm^2 (2 lb./ft.^2). They can be pulled apart very easily by tidal force (or any other substantial force, for that matter). Some 25 comets have been observed to split over the past two centuries. In other cases two or more comets have been discovered in nearly the same orbit, and calculations have indicated that they were once a single comet. A few of these cases have been obviously attributable to the tidal forces of Jupiter (Comet Brooks 2 and Comet Shoemaker–Levy 9) or the Sun (the Kreutz comet family), while other splittings have to be attributed to less obvious causes. For example, the loss of material from an active comet, which tends to occur from a few localized areas, is bound to weaken it. It may be that a rapidly rotating comet can be weakened to the point where the centrifugal force is sufficient to cause large pieces to break off.

The Kreutz family is the name given to many comets which closely approach the Sun from one direction in space. They always approach the Sun to within 3 million km or less, and some have actually hit the Sun. The family was named for Heinrich Kreutz who published extensive monographs on three of these comets and supported the idea that they had a common origin, perhaps in a giant comet observed in 372 B.C. Today the Kreutz family has eight definite, well–studied members; 16 probable members (that are listed as probable only because they didn't survive passage within 800,000 km of the Sun to permit further study); and three more possible members. Extensive work by Brian Marsden suggests that all of these may have resulted from the splitting of two comets around 1100 A.D., which in turn may have been the parts of the great comet of 372 B.C. Those Kreutz fragments which survive their encounters with the Sun are often found to have split yet again!

The classic Roche limit for a (fluid) body of density 1 g/cm^3 approaching Jupiter is about 119,000 km above the cloud tops of the planet. It is about 169,000 km for a body having a density of 0.5 g/cm^3. More complete modern theories making different assumptions result in a somewhat smaller limit. In 1886 Comet Brooks 2 came within 72,000 km of Jupiter's clouds and split into two pieces. In July 1992 Comet Shoemaker–Levy 9 came within about 25,000 km of Jupiter's clouds and fragmented into 21 or more large pieces and an enormous amount of smaller debris down to micron or submicron size. Details of this last event follow.

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4. The Discovery and Early Study of Shoemaker–Levy 9

Comet Shoemaker–Levy 9 was discovered photographically by the husband and wife scientific team of Carolyn S. and Eugene M. Shoemaker and David H. Levy on March 24, 1993, using the 0.46–m (18–in.) Schmidt telescope at Palomar Observatory in California. Its discovery was a serendipitous product of their continuing search for *near–Earth objects*, and the *9* indicates that it was the ninth short–period comet (period less than 200 years) discovered by this team. Near–Earth objects are bodies whose orbits come nearer to the Sun than that of Earth and hence have some potential for collisions with Earth. The appearance of the comet was reported as most unusual; the object appeared as a dense, linear bar about 1 arc minute long and had a fainter, wispy tail. (A circle is divided into 360 degrees, each degree into 60 minutes, and each minute into 60 seconds. The word arc is added to denote an angular measure rather than time. The diameter of the Moon is near 30 arc minutes, for example, while the apparent diameter of Jupiter when closest to Earth is 50 arc seconds.) The comet's brightness was reported as about magnitude 14, more than a thousand times too faint to be seen with the naked eye.

The existence of this object was soon confirmed by James V. Scotti of the Spacewatch program at the University of Arizona, and the International Astronomical Union's Central Bureau for Astronomical Telegrams immediately issued Circular No. 5725 reporting the discovery as a new comet, giving it the provisional designation of 1993e (the fifth comet discovered or recovered in 1993). Scotti reported at least five condensations in a long, narrow train about 47 arc seconds in length and about 11 arc seconds in width, with dust trails extending 4.20 arc minutes to the east and 6.89 arc minutes to the west and tails extending about 1 arc minute from elements of the nuclear train. Bureau director Brian G. Marsden noted that the comet was some 4 arc minutes from Jupiter and that its motion suggested that it could be near Jupiter's distance from the Sun.

By March 27 Marsden had enough positions to attempt to derive possible orbits. One elliptical solution gave a close approach to Jupiter in July 1992. Also on March 27, Jane Luu and David Jewitt took an image with the 2.2–m telescope on Mauna Kea in Hawaii that showed as many as 17 separate sub–nuclei strung out like pearls on a string 50 arc seconds long, and this was reported in Circular No. 5730 two days later. Figure 4 shows an early image taken by Scotti on March 30, 1993. This long exposure (440 seconds on a CCD detector) brings out the faint detail of the debris field, though it overexposes the individual nucleus fragments. Figure 5 is an image from the Hubble Space Telescope (HST), taken by Harold A.

Weaver and collaborators on July 1, 1993 (before the HST repair mission), that clearly shows at least 15 individual fragments in one image frame of the train.

In IAU Circular No. 5744, dated April 3, 1993, Marsden used positions covering a period of 17 days (including two prediscovery positions from March 15) and was able to report that no orbit of very long period (near parabolic) was possible. The orbit had to be an ellipse of rather small eccentricity relative to the Sun and relatively short period. Since it was not at all obvious where the center of mass of this new comet lay, most observers were just reporting the position of what appeared to be the center of the train. This made an accurate orbit (or orbits) difficult to determine. Marsden suggested that a very close approach to Jupiter in 1992 continued to be a distinct possibility, and the orbit he chose to publish was one with the comet at least temporarily in orbit around Jupiter.

By May 22 Marsden had almost 200 positions of the center of the train. In Circular No. 5800 he reported on an orbit computed May 18 by Syuichi Nakano that showed the comet approaching within 120,000 km of Jupiter on July 8, 1992, and approaching again, this time within 45,000 km of the center of Jupiter, on July 25, 1994. Marsden noted that this distance was less than the radius of Jupiter. In other words, the comet, or at least parts of it, could very well hit Jupiter.

By October 18, 1993, Paul W. Chodas and Donald K. Yeomans were able to report at the annual American Astronomical Society's Division of Planetary Sciences meeting that the probability of impact for the major fragments of Shoemaker–Levy 9 was greater than 99%. The fragments apparently would hit over a period of several days, centered on July 21.2, on the night side of Jupiter at latitude 44° S and longitude 35° past the midnight meridian, according to available observations. This unfortunately is also the back side of Jupiter as viewed from Earth. The 1992 approach to Jupiter that disrupted the comet was calculated to have been at a distance of 113,000 km from the planet's center and only 42,000 km above its cloud tops. Furthermore, they found that the comet had been in a rapidly changing orbit around Jupiter for some time before this, probably for at least several decades. It did not fragment during earlier approaches to Jupiter, however, because these were at much greater distances than that of 1992.

After recovery of the comet on December 9, following the period during which it was too near to the Sun in the sky to observe, Chodas and Yeomans found that the probability was greater than 99.99% that all the large fragments will hit Jupiter. The encounter period is now centered on July 19.5, and orbits for individual fragments are uncertain by about 0.03 days (1 s). The impact site has moved closer to the limb of Jupiter, now near 75° from the midnight meridian and only a few degrees beyond the dark limb as seen from Earth, but all pieces still impact on the back side. The 1992 approach that split the comet is now calculated to have occurred on July 7.84 and only 25,000 km (15,500 mi.) above the clouds. These data now cover a much longer time base and are based upon calculations for individual fragments. They are unlikely to change significantly in the future. The comet probably approached Jupiter no nearer than about 9 million km in the orbit prior to that of 1992.

In a comprehensive paper prepared for The Astronomical Journal, Zdenek Sekanina, Chodas, and Yeomans report on the details of the breakup of Shoemaker–Levy 9 as calculated from the positions, motions, and brightness of the fragments and debris. They used data from Jewitt, Luu, and Chen taken in Hawaii, Scotti in Arizona, and Weaver's Hubble Space Telescope (HST) observing team. For example, the 11 brightest fragments as measured with the HST, visual (V) magnitude 23.7–24.8 or about 15 million times too faint to be seen by the naked eye, had the brightness one would expect from spheres 4.3 down to 2.5 km in diameter, assuming a normal cometary reflectivity for the fragments (about 4%). Of course the fragments are not spheres, since tidal disruption tends to occur in planes perpendicular to the direction of the object causing the disruption (Jupiter) and since comets generally are not spherical to begin with. Nevertheless, adding up the sizes of these 11 fragments, the other fragments not precisely measured, and all of the debris making up the trails and tails, suggests that the original comet must have been at least 9 km in average diameter, and it could have been somewhat larger. This was a good–sized comet, about the same size as Comet Halley.

When comets split, the pieces do not go flying apart at a high velocity, each to immediately go into its own independent orbit. The escape velocity from a non–rotating spherical comet 5 km in radius with a density of 0.5 g/cm^3 (half that of water) is 2.65 m/s (6.5 mph). If suddenly freed of gravity and molecular bonds, a particle at the equator of that 10–km body, assuming a rotation period of 12 hours, would depart with a velocity of only 0.72 m/s (1.6 mph) relative to the center of the comet. Some comets appear to rotate more rapidly than once per half day, while many, such as Halley, rotate more slowly. In any case the centrifugal force on unattached pieces of material lying on the surface of a rotating comet is not normally sufficient to overcome the gravity holding them there. Pieces do not fly off of the nucleus spontaneously. Even when the tidal forces overcome self– gravity the pieces separate slowly, and they continue to interact gravitationally. More important, the pieces bang into one another, changing their velocities and perhaps fragmenting further.

In the case of Shoemaker–Levy 9, Sekanina, Chodas, and Yeomans estimate that although fragmentation probably began before closest approach to Jupiter, dynamic independence of the pieces didn't occur until almost two hours after closest approach. For a period of at least two to three hours, collisions dominated the dynamics of all but the largest pieces, with each small grain suffering some 10 collisions per second and the bigger pieces being subjected to many times this number of low velocity impacts by the small particles. All of this converted the original rotational velocities of the bits and pieces of 0–2 mph into a random "equilibrium" velocity distribution, with some smaller pieces having velocities several times their original velocity. Once the pieces stopped hitting one another, each continued to move in its own independent orbit determined mainly by the gravity of Jupiter and the Sun. The pressure of light from the Sun also had a significant effect upon the smallest particles, creating a broad dust tail just as happens in a normal comet. There has been no evidence of the presence of gases from Shoemaker–Levy 9, either direct spectroscopic evidence or motion of the dust particles that cannot otherwise be explained. This is not to say that there are no gases, only that there is no evidence for them. The only direct evidence we have that Shoemaker–Levy 9 is really a comet and not an asteroid is the fact that it broke up so easily! Asteroids are not thought to be so fragile.

It is unlikely that the exact circumstances of the breakup of Shoemaker–Levy 9 will ever be known with certainty. However, the physical model needed to reproduce the train (of individual large fragments), the trails (of debris on either side of the train), and the tails (of very small particles in the anti–Sun direction) in many images like those shown in Figures 4 and 5 does set limits on the separation time, sizes, and velocities of the pieces and particles making up each element. The model of Sekanina, Chodas, and Yeomans, the most complete at this writing, suggests that the original comet cannot have been much smaller than 9 km in mean diameter, that it probably was rotating quite rapidly (perhaps once in eight hours), and that the breakup, as defined by dynamical independence from collisions and limited mutual gravitational effects, was not completed until about two hours after the closest approach to Jupiter. The comet nucleus was probably not very spherical or the debris trails on either side of the train of nucleus fragments would be nearly equal in length, which they are not. After the collisions ceased, the motion of the largest fragments was dominated by Jupiter, with those fragments closest to Jupiter at breakup remaining closest and therefore moving with a shorter period in accordance with basic mechanics. The fragment that started nearest to Jupiter will be the first to return to Jupiter and hit the planet.

All of the large fragments were soon strung out in nearly a straight line that pointed at Jupiter, and they will remain so until colliding with the planet (see Figure 6). H. J. Melosh and P. Schenk have offered the intriguing suggestion that linear chains of craters observed on Jupiter's satellites Ganymede and Callisto are the product of impacts by earlier comets fragmented by Jupiter.

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5. The Planet Jupiter

Jupiter is the largest of the nine planets, more than 10 times the diameter of Earth and more than 300 times its mass. In fact the mass of Jupiter is almost 2.5 times that of all the other planets combined. Being composed largely of the light elements hydrogen and helium, its mean density is only 1.314 times that of water. The mean density of Earth is 5.245 times that of water. The pull of gravity on Jupiter at the top of the clouds at the equator is 2.4 times as great as gravity's pull at the surface of Earth at the equator. The bulk of Jupiter rotates once in 9h 55.5m, although the period determined by watching cloud features differs by up to five minutes due to intrinsic cloud motions.

The visible surface of Jupiter is a deck of clouds of ammonia crystals, the tops of which occur at a level where the pressure is about half that at Earth's surface. The bulk of the atmosphere is made up of 89% molecular hydrogen (H2) and 11% helium (He). There are small amounts of gaseous ammonia (NH3), methane (CH4), water (H2O), ethane (C2H6), acetylene (C2H2), carbon monoxide (CO), hydrogen cyanide (HCN), and even more exotic compounds such as phosphine (PH3) and germane (GeH4). At levels below the deck of ammonia clouds there are believed to be ammonium hydro–sulfide (NH4SH) clouds and water crystal (H2O) clouds, followed by clouds of liquid water. The visible clouds of Jupiter are very colorful. The cause of these colors is not yet known. Contamination by various polymers of sulfur (S3, S4, S5, and S8), which are yellow, red, and brown, has been suggested as a possible cause of the riot of color, but in fact sulfur has not yet been detected spectroscopically, and there are many other candidates as the source of the coloring.

The meteorology of Jupiter is very complex and not well understood. Even in small telescopes, a series of parallel light bands called zones and darker bands called belts is quite obvious. The polar regions of the planet are dark. (See Figure 7.) Also present are light and dark ovals, the most famous of these being the *Great Red Spot*. The Great Red Spot is larger than Earth, and although its color has brightened and faded, the spot has persisted for at least 162.5 years, the earliest definite drawing of it being Schwabe's of Sept. 5, 1831. (There is less positive evidence that Hooke observed it as early as 1664.) It is thought that the brighter zones are cloud–covered regions of upward moving atmosphere, while the belts are the regions of descending gases, the circulation driven by interior heat. The spots are thought to be large–scale vortices, much larger and far more permanent than any terrestrial weather system.

The interior of Jupiter is totally unlike that of Earth. Earth has a solid crust *floating* on a denser mantle that is fluid on top and solid beneath, underlain by a fluid outer core that extends out to about half of Earth's radius and a solid inner core of about 1,220–km radius. The core is probably 75% iron, with the remainder nickel, perhaps silicon, and many different metals in small amounts. Jupiter on the other hand may well be fluid throughout, although it could have a small solid core (say up to 15 times the mass of Earth!) of heavier elements such as iron and silicon extending out to perhaps 15% of its radius. The bulk of Jupiter is fluid hydrogen in two forms or phases, liquid molecular hydrogen on top and liquid metallic hydrogen below; the latter phase exists where the pressure is high enough, say 3–4 million atmospheres. There could be a small layer of liquid helium below the hydrogen, separated out gravitationally, and there is clearly some helium mixed in with the hydrogen. The hydrogen is convecting heat (transporting heat by mass motion) from the interior, and that heat is easily detected by infrared measurements, since Jupiter radiates twice as much heat as it receives from the Sun. The heat is generated largely by gravitational contraction and perhaps by gravitational separation of helium and other heavier elements from hydrogen, in other words, by the conversion of gravitational potential energy to thermal energy. The moving metallic hydrogen in the interior is believed to be the source of Jupiter's strong magnetic field.

Jupiter's magnetic field is much stronger than that of Earth. It is tipped about 11° to Jupiter's axis of rotation, similar to Earth's, but it is also offset from the center of Jupiter by about 10,000 km (6,200 mi.). The magnetosphere of charged particles which it affects extends from 3.5 million to 7 million km in the direction toward the Sun, depending upon solar wind conditions, and at least 10 times that far in the anti–Sun direction. The plasma trapped in this rotating, wobbling magnetosphere emits radio frequency radiation measurable from Earth at wavelengths from 1 m or less to as much as 30 km. The shorter waves are more or less continuously emitted, while at longer wavelengths the radiation is quite sporadic. Scientists will carefully monitor the Jovian magnetosphere to note the effect of the intrusion of large amounts of cometary dust into the Jovian magnetosphere.

The two Voyager spacecraft discovered that Jupiter has faint dust rings extending out to about 53,000 km above the atmosphere. The brightest ring is the outermost, having only about 800–km width. Next inside comes a fainter ring about 5,000 km wide, while very tenuous dust extends down to the atmosphere. Again, the effects of the intrusion of the dust from Shoemaker–Levy 9 will be interesting to see, though not easy to study from the ground.

The innermost of the four large satellites of Jupiter, Io, has numerous large volcanos that emit sulfur and sulfur dioxide. Most of the material emitted falls back onto the surface, but a small part of it escapes the satellite. In space this material is rapidly dissociated (broken into its atomic constituents) and ionized (stripped of one or more electrons). Once it becomes charged, the material is trapped by Jupiter's magnetic field and forms a torus (donut–shape) completely around Jupiter in Io's orbit. Accompanying the volcanic sulfur and oxygen are many sodium ions (and perhaps some of the sulfur and oxygen as well) that have been sputtered (knocked off the surface) from Io by high energy electrons in Jupiter's magnetosphere. The torus also contains protons (ionized hydrogen) and electrons. It will be fascinating to see what the effects are when large amounts of fine particulates collide with the torus.

Altogether, Jupiter has 16 known satellites. The two innermost, Metis and Adrastea, are tiny bodies, having radii near 20 and 10 km respectively, that interact strongly with the rings and in fact may be the source of the rings. That is, the rings may be debris from impacts on the satellites. Amalthea and Thebe are still small, having mean radii of 86.2 and about 50 km, respectively, but they are close to Jupiter and may serve as useful reflectors of light from some of the impacts. The Galilean satellites (the four moons discovered by Galileo in 1610), Io, Europa, Ganymede, and Callisto, range in radius from 1,565 km (Europa) to 2,634 km (Ganymede). (Earth's Moon has a radius of 1,738 km.) They lie at distances of 421,700 km (Io) to 1,883,000 km (Callisto) from Jupiter. These objects will serve as the primary reflectors of light from the impacts for those attempting to indirectly observe the actual impacts. The outer eight satellites are all tiny (less than 100–km radius) and at large distances (greater than 11 million km) from Jupiter. They are expected to play no role in impact studies.

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6. The Final Orbit of Shoemaker–Levy 9

The motion of Comet Shoemaker–Levy 9 can technically be described as chaotic, which means that calculations based upon the input of comet positions having very tiny differences (small input errors) causes large differences in the results of calculations of the subsequent motion and the apparent prior motion. Large perturbations caused by successive close approaches to Jupiter have resulted in each orbit being different in size, shape, and orientation. The orbits have not been the simple result of a small body in orbit around a large one but rather the product of a tug of war between Jupiter and the Sun, a classic three--body problem. Near to Jupiter the planet's gravity has dominated the motion, but far from Jupiter the Sun is more important. On July 16, 1993, at apojove (the point farthest from Jupiter) in the current orbit, Shoemaker–Levy 9 was almost 1,200 times as far from Jupiter as at the time of breakup, a distance of 50 million km, equal to a third of the distance of Earth from the Sun. The comet has been in a closed orbit around Jupiter for many decades, but that orbit is far from stable. Figure 8 by Chodas shows what this orbit will look like as viewed from the Sun at the time of impact. It is tipped (inclined) 53° to Jupiter's equator as measured at apojove and is bent about 20° more near to Jupiter. (A three–body orbit rarely lies in one plane like the simple two–body orbit.)

During this final orbit, after breakup in July 1992, Shoemaker– Levy 9 was followed carefully from discovery in March 1993 until the time the comet's angular distance from the Sun became too small to permit observations. The last useful astrometric (positional) observations reported before the fragments were lost in the glare of the Sun were made on July 11. The comet was recovered (found again after almost five months without observations) by Scotti and Tom Gehrels on December 9, with the comet rising above the horizon a bit more than three hours before the Sun in the morning sky. (The comet is so faint that it cannot be observed in twilight or too low on the horizon.) The quality of the predictions for the time of impact of the individual fragments on Jupiter will depend upon the number of high–quality astrometric observations of each comet fragment made between December 1993 and the time of impact. A week before the impacts the times should be known at least to 110 minutes (with 50% confidence), improving to perhaps 15 minutes a half day before impact.

At a fall planetary astronomy meeting (DPS) Jewitt, Luu, and Chen exhibited an image showing 21 distinct fragments in the Shoemaker– Levy 9 nucleus train. At discovery in March, this train was about 50 arc seconds or 162,000 km in length as projected on the sky. This angular distance had increased by about 40% (and the true linear distance by about 50%, since Jupiter was then farther from Earth) by the time the comet was lost in the glare of the Sun in July. The spreading is caused mainly by the fact that the piece closest to Jupiter at breakup was some 9 km closer than the farthest piece (the diameter of the comet) and therefore entered a faster orbit. The orbits are all so elongated that from Earth they appear to be nearly a straight line with the fragments strung out along it. The fragment nearest to Jupiter at breakup remains nearest to it and will be the first to impact. At this writing, Chodas and Yeomans predict that the train will reach an apparent length of some 1,286 arc seconds at the time the first of the fragments enters Jupiter's atmosphere. The true length of the train will be 4,900,000 km at that time, and it will require 5.5 days for all of the major fragments to impact.

The new data taken following solar conjunction (the closest apparent approach to the Sun as projected against the sky) more than doubled the length of time since discovery for which cometary positions were available. With this new data, it appears that the impacts will be centered on about July 19.5, a day and a half earlier than the first predictions. The approach to Jupiter that shattered the comet appears to have been even closer than first thought, about 96,000 km from the planet's center and only 25,000 km above the clouds. The revised orbit has also moved the impact points closer to the visible hemisphere, but unfortunately still on the back side as seen from Earth. The brightest fragment, of which there is some indication that it itself is fragmented, will impact on about July 20.78 and contains about 10% of the total mass of the comet. The other 20 observed fragments contain more than 80% of the mass. The remaining mass is contained in all of the dust and small pieces in the train, the trails, and the tails. Most of this mass also will hit Jupiter over a period of several months beginning about July 10, but it probably will cause few or no detectable effects.

Meanwhile, the dust trails of small debris will continue to spread, as will the major fragments. The east–northeast trail is expected to reach a maximum apparent length of some 70 arc minutes in late June of 1994 and then decrease again in apparent length with the tip turning around into a V shape. The west–southwest trail may reach a length of almost 100 arc minutes before impacts begin. Only the larger trail material will actually impact Jupiter. The earliest dust will begin to hit about July 10, and impacts will continue into October. The smaller dust will be moved into the tail by solar radiation pressure and will miss the planet completely.

If upon further study it is found that the pieces of Shoemaker– Levy 9 have continued to fragment, then predicting impact times will be much more difficult and the predictions less reliable. Such continued fragmentation of pieces already badly fractured is very possible, but fragmentation in the last day or two, when it is most likely to occur, will have no significant effect on the predicted times of impact. The pieces typically separate with a velocity of less than a meter per second. There are 86,400 seconds in a day, so even pieces separating at a full meter per second would be only 86.4 km apart after one day. Moving jointly at a velocity which reaches 60 km/s at impact, the pieces would hit within a few seconds of each other. The effect of further splitting upon the impact phenomena would be far greater and is discussed in the next section.

Figure 9 by David Seal shows the final segment of the comet fragment's trajectories. They will impact near a latitude of 44° S and a longitude 70° past the midnight meridian, still 10° beyond the limb of Jupiter as seen from Earth, impacting the atmosphere at an angle of about 42°. from vertical.

Observing conditions from Earth will not be ideal at the time of the impacts, since there will be only about two hours of good observing time for large telescopes at any given site after the sky gets good and dark and before Jupiter comes too close to the horizon to observe. At least it will be summer in the northern hemisphere, and there will be a better chance for good weather where many observatories are located. With 21 pieces hitting over a 5.5–day period, there will be an impact on average about every 6 hours, so any given site should have about one chance in three of observing at the actual time of an impact each night. Since the impacts will be on the back side of Jupiter, light from the impacts can only be observed by reflection from Jupiter's moons or perhaps from the rings or the dust comae of the comet fragments. Those attempting observations of the effects of the impacts on Jupiter can begin about 20 minutes after the impacts, when the impact area rotates into view from Earth.

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7. The Collisions

Exactly what will happen as the fragments of Shoemaker–Levy 9 enter the atmosphere of Jupiter is very uncertain, though there are many predictions. If the process were better understood, it would be less interesting. Certainly scientists have never observed anything like this event. There seems to be complete agreement only that the major fragments will hit Jupiter and that these collisions will occur on the back side of Jupiter as seen from Earth.

Any body moving through an atmosphere is slowed by atmospheric drag, by having to push the molecules of that atmosphere out of the way. The kinetic energy lost by the body is given to the air molecules. They move a bit faster (become hotter) and in turn heat the moving body by conduction. This frictional process turns energy of mass motion (kinetic energy) into thermal energy (molecular motion). The drag increases roughly as the square of the velocity. In any medium a velocity is finally reached at which the atmospheric molecules can no longer move out of the way fast enough and they begin to pile up in front of the moving body. This is the speed of sound (Mach 1 –– 331.7 m/s or 741 mph in air on Earth at sea level). A discontinuity in velocity and pressure is created which is called a shock wave. Comet Shoemaker–Levy 9 will enter Jupiter's atmosphere at about 60 km/s, which would be about 180 times the speed of sound on Earth (Mach 180!) and is about 50 times the speed of sound even in Jupiter's very light, largely hydrogen atmosphere.

At high supersonic velocities (much greater than Mach 1) enough energy is transferred to an intruding body that it becomes incandescent and molecular bonds begin to break. The surface of the solid body becomes a liquid and then a gas. The gas atoms begin to lose electrons and become ions. This mixture of ions and electrons is called a plasma. The plasma absorbs radio waves and is responsible for the communication blackouts that occur when a spacecraft such as the Space Shuttle reenters Earth's atmosphere. The atmospheric molecules are also dissociated and ionized and contribute to the plasma. At higher temperatures, energy transfer by radiation becomes more important than conduction. Ultimately the temperatures of the plasma and the surface of the intruding body are determined largely by the radiation balance. The temperature may rise to 50,000 K (90,000 F) or more for very large bodies such as the fragments of Shoemaker–Levy 9 entering Jupiter's atmosphere at 60 km/s. The loss of material as gas from the impacting body is called thermal ablation. The early manned spacecraft (Mercury, Gemini, and Apollo) had *ablative heat shields* made of a material having low heat conductivity (through to the spacecraft) and a high vaporization temperature (strong molecular bonds). As this material was lost, as designed, it carried away much of the orbital energy of the spacecraft reentering Earth's atmosphere.

There are other forms of ablation besides thermal ablation, the most important being loss of solid material in pieces. In a comet, fragile to begin with and further weakened and/or fractured by thermal shock and by melting, such spallation of chips or chunks of material has to be expected. Turbulence in the flow of material streaming from the front of the shock wave can be expected to strip anything that is loose away from the comet and send it streaming back into the wake. The effect of increasing temperature, pressure, and vibration on an intrinsically weak body is to crush it and cause it to flatten and spread. Meanwhile the atmosphere is also increasing in density as the comet penetrates to lower altitudes. All of these processes occur at an ever increasing rate (mostly exponentially).

On Earth a sizable iron meteoroid or even some relatively low velocity stony meteoroids can survive all of this and impact the surface, where we collect them for study and exhibition. (Small bodies traveling in space are called meteoroids. The visible phenomena which occur as a meteoroid enters the atmosphere is called a meteor. Surviving solid fragments are called meteorites. There is no sharp size distinction between meteoroids and asteroids. Normally, if the body has been detected telescopically before entering the atmosphere, it has been called an asteroid.) Many meteoroids suffer what is called a *terminal explosion* when crushed while still many kilometers above the ground. This is what happened in Tunguska, Siberia, in 1908. There a body with a mass of some 109 kg (2.2 billion lb.) and probably 90 to 190 m in diameter entered Earth's atmosphere at a low angle with a velocity of less than 15 km/s. It exploded at an altitude of perhaps 5–10 km. This explosion, equivalent to 10–20 megatons of TNT, combined with the shock wave generated by the body's passage through the atmosphere immediately before disruption, leveled some 2,200 km^2 of Siberian forest. The Tunguska body had a tensile strength of some 2 x 10^8 dynes/cm^2, more than 100,000 times the strength of Shoemaker–Levy 9, but no surviving solid fragments of it (meteorites) have ever been found. The fragile Shoemaker–Levy 9 fragments entering an atmosphere of virtually infinite depth at a much higher velocity will suffer almost immediate destruction. The only real question is whether each fragment may break into several pieces immediately after entry, and therefore exhibit multiple smaller explosions, or whether it will survive long enough to be crushed, flattened, and obliterated in one grand explosion and terminal fireball.

Scientists have differed in their computations of the depths to which fragments of given mass will penetrate Jupiter's atmosphere before being completely destroyed. If a terminal explosion occurs above the clouds, which are thought to lie at a pressure level of about 0.5 bar or roughly 0.5 Earth atmosphere (see

Section 5), then the explosion will be very bright and easily observable by means of light reflected from Jupiter's satellites. Using ablation coefficients derived from observation of many terrestrial fireballs, Sekanina predicts that the explosions indeed will occur above the clouds. Mordecai–Mark Mac Low and Kevin Zahnle have made calculations using an astrophysical hydrodynamic code (ZEUS) on a supercomputer. They assume a fluid body as a reasonable approximation to a comet, since comets have so little strength, and they predict that the terminal explosions will occur near the 10–bar level, well below the clouds. Others have suggested still deeper penetration, but most calculations indicate that survival to extreme depths is most unlikely. The central questions then appear to be whether terrestrial experience with lesser events can be extrapolated to events of such magnitude and whether all the essential physics has been included in the supercomputer calculations. We can only wait and observe what really happens, letting nature teach us which predictions were correct.

O.K. So an explosion occurs at some depth. What does that do? What happens next? Sekanina calculates that about 93% of the mass of a 10^13–kg fragment remains one second before the terminal explosion and the velocity is still almost 60 km/s. During that last second the energy of perhaps 10,000 100–megaton bombs is released. Much of the cometary material will be heated to many tens of thousands of degrees, vaporized, and ionized along with a substantial amount of Jupiter's surrounding atmosphere. The resulting fireball should balloon upward, even fountaining clear out of the atmosphere, before falling back and spreading out into Jupiter's atmosphere, imitating in a non–nuclear fashion some of the atmospheric hydrogen bomb tests of the 1950s. Once again, the total energy release here will be many thousands of times that of any hydrogen bomb ever tested, but the energy will be deposited initially into a much greater volume of Jupiter's atmosphere, so the energy density will not be so high as in a bomb, and, of course, there will be no gamma rays or neutrons (nuclear radiation or particles) flying about. The energy of these impacts will be beyond any prior experience. The details of what actually occurs will be determined by the observations in July 1994, if the observations are successful.

If differential gravitation (tidal forces) should further fragment a piece of the comet, say an hour or two before impact, the pieces can be expected to hit within a second of each other. In one second a point at 44° latitude on Jupiter will rotate 9 km (5.6 mi.), however, so the pieces would enter the atmosphere some distance apart. Smaller pieces will explode at higher altitudes but not so spectacularly. If smaller pieces do explode above the clouds, they may be more visible than larger pieces exploding below the clouds. It is also possible that implanting somewhat less energy density over a wider volume of atmosphere might create a more visible change in Jupiter's atmosphere. Sekanina notes that pieces smaller than about 1.3–km mean radius should not be further fragmented by tidal forces unless they were already weakened by earlier events.

One of the more difficult questions to answer is just how bright these events will be. Terrestrial fireballs have typically exhibited perhaps 1% luminous efficiency. In other words about 1% of the total kinetic energy has been converted to visible light. The greater magnitude of the Jupiter impacts may result in more energy appearing as light, but let's assume the 1% efficiency. Then Sekanina calculates that a 10^13–kg fragment, a reasonable value for the largest piece, will reach an apparent visual magnitude of −10 during the terminal explosion. This is 1,000 times Jupiter's normal brilliance and only 10 times fainter than the full moon! Sekanina, of course, calculates that the explosions will occur above the clouds. And, remember that, unfortunately, these impacts will occur on Jupiter's back side as seen from Earth. There will be no immediate visible effect on the appearance of Jupiter. The light of the explosion may be seen reflected from the Galilean satellites of Jupiter, if they are properly placed at the times of impacts. Ganymede, for example, might brighten as much as six times, while Io could brighten to 35 times its normal brilliance for a second before fading slowly, if the explosions occur above the clouds. This would certainly be visible in an amateur telescope and could conceivably be visible to the naked eye at a dark mountain site as a tiny flash next to Jupiter at the location of the normally invisible satellite. Emphasis on tiny! The brightness of explosions occurring below the clouds will be attenuated by a factor of at least 10,000, making them most difficult to observe. In the best of cases, these events will be spectacles for the mind to imagine and big telescopes to observe, not a free fireworks display.

The most recent predictions are that at least some of the impacts will occur very close to the planetary limb, the edge of the planet's disk as seen from Earth. That edge still has 11! to rotate before it comes into sunlight. This means that the tops of some of the plumes associated with the rising fireballs may be just visible, although with a maximum predicted height of 3,000 km (0.8 arc second as projected on the sky) they will be just peeking over the limb. The newly repaired Hubble Space Telescope (HST), with its high resolution and low scattered light, may offer the best chance to see such plumes. By the time they reach their maximum altitude the plumes will be transparent (optically thin) and not nearly so bright as they were near the clouds. Some means of blocking out the bright light from Jupiter itself may be required in order to observe anything. A number of observers plan to look for evidence of plumes and to attempt to measure their size and brightness.

It also is difficult to predict the effects of the impacts on Jupiter's atmosphere. Robert West points out that a substantial amount of material will be deposited even in the stratosphere of Jupiter, the part of the atmosphere above the visible clouds where solar heating stabilizes the atmosphere against convection (vertical motion). Part of this material will come directly from small cometary grains, which vaporize during entry and recondense just as do meteoritic grains in the terrestrial atmosphere. Part will come from volatiles (ammonia, water, hydrogen sulfide, etc.) welling up from the deeper atmosphere as a part of the hot buoyant fireballs created at the time of the large impact events. Many millimeter–sized or larger pieces from the original breakup will also impact at various times for months and over the entire globe of Jupiter. There is relatively little mass in these smaller pieces, but it might be sufficient to create a haze in the stratosphere.

James Friedson notes that the fireball created by the terminal explosion will expand and balloon upward and perhaps spew vaporized comet material and Jupiter's entrained atmospheric gas to very high altitudes. The fireball may carry with it atmospheric gases that are normally to be found only far below Jupiter's visible clouds. Hence the impacts may give astronomers an opportunity to detect gases which have been hitherto hidden from view. As the gaseous fireball rises and expands it will cool, with some of the gases it contains condensing into liquid droplets or small solid particles. If a sufficiently large number of particles form, then the clouds they produce may be visible from Earth–based telescopes after the impact regions rotate onto the visible side of the planet. These clouds may provide the clearest indication of the impact locations after each event.

After the particles condense, they will grow in size by colliding and sticking together to form larger particles, eventually becoming sufficiently large to rain out of the visible part of the atmosphere. The length of time spent by the cloud particles at altitudes where they can be seen will depend principally on their average size; relatively large particles would be visible only for a few hours after an impact, while small particles could remain visible for several months. Unfortunately, it is very difficult to predict what the number and average size of the particles will be. A cloud of particles suspended in the atmosphere for many days may significantly affect the temperature in its vicinity by changing the amount of sunlight that is absorbed in the area. Such a temperature change could be observed from Earth by searching for changes in the level of Jupiter's emitted infrared light.

Glenn Orton notes that large regular fluctuations of atmospheric temperature and pressure will be created by the shock front of each entering fragment, somewhat analogous to the ripples created when a pebble is tossed into a pond, and will travel outward from the impact sites. These may be observable near layers of condensed clouds in the same way that regular cloud patterns are seen on the leeward side of mountains. Jupiter's atmosphere will be sequentially raised and lowered, creating a pattern of alternating cloudy areas where ammonia gas freezes into particles (the same way that water condenses into cloud droplets in our own atmosphere) and clear areas where the ice particles warm up and evaporate back into the gas phase. If such waves are detected, measurement of their wavelength and speed will allow scientists to determine certain important physical properties of Jupiter's deep atmospheric structure that are very difficult to measure in any other way.

Whether or not wave clouds appear, the ripples spreading from the impact sites will produce a wave structure in the temperature at a given level that may be observable in infrared images. In addition there should be compression waves, alternate compression and rarefaction in the atmospheric pressure, which could reflect from and refract within the deeper atmosphere, much as seismic waves reflect and refract due to density changes inside Earth. Orton suggests that these waves might be detected breaking up in the shallow atmosphere on the opposite side of the planet from the impacts. Others suggest the possibility of measuring the small temperature fluctuations wherever the waves surface, but this requires the ability to map fluctuations in Jupiter's visible atmosphere of a few millikelvin (a few thousandths of a degree). Detection of any of these waves will require a very fine infrared array detector (a thermal infrared camera).

Between the water and other condensable gases (volatiles) brought with the comet fragments and those exhumed by the rising fireballs, it is fairly certain that a cloud of condensed material will form at the location of the impacts themselves, at high altitudes where such gases seldom, if ever, exist in the usual course of things. It may be difficult to differentiate between the color or brightness of these condensates and any bright material below them in spectra at most visible wavelengths. However, at wavelengths where gaseous methane and hydrogen absorb sunlight, a distinction can easily be made between particles higher and lower in the atmosphere, because the higher particles will reflect sunlight better. Much of the light is absorbed before reaching the lower particles. Observing these clouds in gaseous absorption bands will then tell us how high they lie in the atmosphere, and observations over a period of time will indicate how fast high–altitude winds are pushing them. The speed with which these clouds disappear will be a measure of particle sizes in the clouds, since large particles settle out much faster than small ones, hours as compared to days or months.

Orton also notes that in the presence of a natural wind shear (a region with winds having different speeds and/or directions) such as exists commonly across the face of Jupiter, a long–lived cyclonic feature can be created which is actually quite stable. It may gain stability by being fed energy from the wind shear, in much the same way that the Great Red Spot and other Jovian vortices are thought to be stabilized. Such creation of new, large, fixed storm systems is somewhat controversial, but this is a most intriguing possibility!

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8. How Can These Impacts and Their Consequences be Studied?

Space–Based

There are at least four spacecraft –– Galileo, Ulysses, Voyager 2, and Clementine –– with some potential to observe the Jovian impacts from different vantage points than that of Earth. There is also the Hubble Space Telescope (HST), in orbit around Earth, which will view the event with essentially the same geometry as any Earth–based telescope. HST, however, has the advantages of perfect seeing (no atmospheric turbulence), very low scattered light, ultraviolet sensitivity, and the ability to observe much more than two hours each day. HST is scheduled to devote considerable time to the observation of Shoemaker–Levy 9 before as well as during the impacts.

The Galileo spacecraft has the best vantage point from which to observe the impacts. It is on its way to Jupiter and will be only 246 million km away from the planet, less than a third the distance of Earth from Jupiter at that time. All of the impacts will occur directly in the field of view of its high resolution camera and 20–25 degrees of Jovian longitude from the limb. Images of Jupiter will be 60 picture elements (pixels) across, although the impact site will still be smaller than the resolution of the camera. Several instruments besides the camera have potential use, including an ultraviolet spectrometer, a near infrared mapping spectrometer, and a photopolarimeter radiometer. This last suite of instruments could acquire light curves (plots of intensity versus time) of the entry and fireball at many wavelengths from ultraviolet to thermal infrared (from wavelengths much shorter than visible light to much longer).

Using Galileo to make these observations will be challenging. The amount of data the spacecraft can transmit back to Earth is limited by the capability of its low–gain antenna and the time available on the receiving antennas of the National Aeronautics and Space Administration's (NASA's) Deep Space Network here on Earth. The commands that tell the spacecraft what to do must be sent up several weeks before the fact and before the impact times are known to better than about 20 minutes with 95% certainty. A later command that simply triggers the entire command sequence may be possible. A lot of data frames can be stored in the Galileo tape recorder, but only about 5% of them can be transmitted back to Earth, so the trick will be to decide which 5% of the data are likely to include the impacts and to have the greatest scientific value, without being able to look at any of them first! After the fact, the impact times should be known quite accurately.

This knowledge can help to make the decisions about which data to return to Earth.

The Ulysses spacecraft was designed for solar study and used a gravity assist from flying close to Jupiter to change its inclination (the tilt of its path relative to the plane of the planets) so it can fly over the poles of the Sun. In July 1994 it will be about 378 million km south of the plane of the planets (the ecliptic) and able to look over the south pole of Jupiter directly at the impact sites. Unfortunately, Ulysses has no camera as a part of its instrument complement. It does have an extremely sensitive receiver of radio frequency signals from 1 to 1000 kHz (kilohertz, or kilocycles in older terminology) called URAP (Unified Radio and Plasma wave experiment). URAP may be able to detect thermal radiation from the impact fireballs once they rise sufficiently high above interference from the Jovian ionosphere (upper atmosphere) and to measure a precise time history of their rapid cooling.

The Voyager 2 spacecraft is now far beyond Neptune (its last object of study back in 1989 after visiting Jupiter in 1979, Saturn in 1981, and Uranus in 1986) and is about 6.4 billion km from the Sun. It can look directly back at the dark side of Jupiter, but the whole of Jupiter is now only two picture elements in diameter as seen by its high–resolution camera, if that instrument were to be used. In fact the camera has been shut down for several years, and the engineers who knew how to control it have new jobs or are retired. It would be very expensive to take the camera out of mothballs and probably of limited scientific value. Voyager does have an ultraviolet spectrometer which is still taking data, and it will probably be used to acquire ultraviolet light curves (brightness versus time) of the impact phenomena. The possibility of using one or two other instruments is being considered, though useful results from them seem less likely.

A new small spacecraft called Clementine was launched on January 25 of this year, intended to orbit the Moon and then proceed on to study the asteroid Geographos. Clementine has good imaging capabilities, but its viewpoint will not be much different from Earth's. The impact sites will still be just over the limb, and Clementine's resolution will be only a few picture elements on Jupiter. Since the spacecraft will be in cruise mode at the time, on its way to Geographos and not terribly busy, it seems probable that attempts will be made to observe blips of light on the limb of Jupiter, from the entering fragments or the fireballs or perhaps light scattered from cometary material (coma) that has not yet entered the atmosphere. Useful light curves could result.

Ground–Based

Many large telescopes will be available on Earth with which to observe the phenomena associated with the Shoemaker– Levy 9 impacts on Jupiter in visible, infrared, and radio wavelengths. Small portable telescopes can fill in gaps in existing observatory locations for some purposes. Imaging, photometry, spectroscopy, and radiometry will certainly be carried out using a multitude of detectors. Many of these attempts will fail, but some should succeed.

Apart from the obvious difficulty that the impacts will occur on the back side of Jupiter as seen from Earth, the biggest problem is that Jupiter in July can only be observed usefully for about two hours per night from any given site. Earlier the sky is still too bright and later the planet is too close to the horizon. Therefore, to keep Jupiter under continuous surveillance would require a dozen observatories equally spaced in longitude clear around the globe. A dozen observatories is feasible, but equal spacing is not. There will be gaps in the coverage, notably in the Pacific Ocean, where Mauna Kea, Hawaii, is the only astronomical bastion.

Measuring the light curve of the entering fragments and the post– explosion fireball can be done only by measuring the light reflected from something else, one of Jupiter's satellites or perhaps the dust coma accompanying the fragment. That dust coma could still be fairly dense out to distances of 10,000 km or more around each fragment. Moving at 60 km/s, it will be almost three minutes before all of the dust also impacts Jupiter. Proper interpretation of such observations will be difficult, however, because the area of the reflector, the coma dust particles, will be changing as the observations are made. Another complication is the brightness of Jupiter itself, which will have to be masked to the greatest extent possible. Observations in visible light reflected from the satellites will be relatively straightforward and can be done with small telescopes and simple photometers or imaging devices. This equipment is small enough that it can be transported to appropriate sites.

Spectroscopy of the entry phenomena via reflected light from one of the Galilean satellites could be used to determine the composition of the comet and the physical conditions in the fireball, if the terminal explosions occur above Jupiter's clouds. If the explosion occurs below the clouds, there will be too little light to do useful spectroscopy with even the largest telescopes.

The impact zone on Jupiter will rotate into sight from Earth about 20 minutes after each impact, though quite foreshortened as initially viewed. Extensive studies of the zone and the area around it can be made at that time. Such studies surely will include imaging, infrared temperature measurements, and spectroscopy using many of the largest telescopes on Earth. These studies will continue for some weeks, if there is any evidence of changes in Jupiter's atmosphere and cloud structure as a result of the impacts.

For example, astronomers will use spectrometers to look for evidence of chemical changes in Jupiter's atmosphere. Some of the species observed might be those only present in the deep atmosphere and carried up by the fireball (if the explosion occurs deep enough). Others will be the result of changes to the chemistry of the upper atmosphere, taking place because of the energy deposited there by the impacts or because of the additional particulates.

The faint rings of Jupiter, mentioned in Section 5, can be usefully observed from the ground at infrared wavelengths. Shoemaker–Levy 9 debris might bring in new ring material by hitting the two small satellites embedded in the rings (Metis and Adrastea). The rings surely will be monitored for some time using infrared imaging array detectors, which are sensitive to wavelengths more than eight times as long as red visible light.

In Section 5, note was made of the Jovian magnetosphere, which makes its presence known at radio wavelengths, and the Io torus of various ions and atoms, which can be mapped spectroscopically. Either or both of these could be affected sufficiently by the intruding dust from Shoemaker–Levy 9 to be detectably changed. Radio telescopes will surely monitor the former and optical telescopes the latter for weeks or months looking for changes. Jupiter's intense electromagnetic environment is responsible for massive auroral emission near the planet's poles and less intense phenomena across the face of the planet. These may also be disrupted by the collisions and/or the dust "invasion," making auroral monitoring a useful observing technique.

In summary, the phenomena directly associated with each impact from entry trail to rising fireball will last perhaps three minutes. The fallback of ejecta over a radius of a few thousand kilometers will last for about three hours. Seismic waves from each impact might be detectable for a day, and atmospheric waves for several days. Vortices and atmospheric hazes could conceivably persist for weeks. New material injected into the Jovian ring system might be detectable for years. Changes in the magnetosphere and/or the Io torus might also persist for some weeks or months. There is the potential to keep planetary observers busy for a long time!

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9. What Do Scientists Expect to Learn from All of This?

To give a simple and succinct answer to the title of this section, scientists hope to learn more about comets, more about Jupiter, and more about the physics of high velocity impacts into a planetary atmosphere. Something has already been learned about comets from the behavior of Shoemaker–Levy 9 during its breakup, as discussed in Section 4. Bits and pieces of what everyone hopes will be learned have been noted in Sections 5 through 8. A more complete summary follows.

If the fragments explode above the clouds, there should be enough light reflected from various Jovian satellites to take spectra of the explosions. Since the atmosphere of Jupiter contains very few heavier elements to contaminate the spectra, they could give a great deal of information about the composition of cometary solids. If the fragments explode below the clouds, then spectroscopy must wait until the impact sites rotate into view from Earth. By that time everything will have cooled a great deal, and the cometary component will have been diluted by mixing with the Jovian atmosphere, making such study difficult. In that case the Jovian material itself may prove of interest, with spectroscopic study giving new knowledge of Jupiter's deeper atmospheric composition.

It seems somewhat more certain that new knowledge of Jupiter's atmosphere will be obtained, even if predictions differ as to exactly what that new knowledge will be. There is nearly unanimous agreement that the impacts will cause observable changes in Jupiter, at least locally at the impact sites. These may include changes in the visible appearance of the clouds, locally or more widely, measurable temperature fluctuations, again locally or more widely, composition changes caused by material brought up from below the clouds (if the fragments penetrate that deeply), and/or chemical reactions brought about by the thermal pulse and the introduction of cometary material. Any dynamic processes such as these will give a new and better understanding of the structure of Jupiter's atmosphere, perhaps of its motion as well as its static structure.

If sufficient material impacts Jupiter's rings or especially the ring satellites, then there should be local brightening caused by the increase in reflecting area due to the introduction of new material. These new ring particles will each take up their own orbits around Jupiter, gradually spreading out and causing local brightening followed by slow fading into the general ring background. Careful mapping of that brightening and fading will reveal a great deal about the structure and dynamics of the rings. Many believe that impacts on those small inner satellites are the source of the rings, the reason for their existence. Enhancement of the rings from Shoemaker–Levy 9 impacts would be strong confirmation of this idea. Similarly, the interaction of cometary dust with the magnetosphere and with the Io torus will be quite informative, if the dust density proves sufficient to cause observable effects. Radio telescopes will be active in the magnetospheric studies, along with optical spectroscopy of the ions and atoms in the torus.

Last, but far from least, the physics of the impact phenomena themselves, determined from the reflected light curves and from spectra, will be most instructive. Note the inability of scientists to agree on the level of Jupiter's atmosphere at which the terminal explosion will occur. (A few even believe that there will be no terminal explosion or that it will occur so deep in that atmosphere as to be completely unobservable.) Entry phenomena on this scale cannot be reproduced, even by nuclear fusion explosions, and have never before been observed. Better knowledge of the phenomena may allow scientists to predict more accurately just how serious could be the results of future impacts of various–sized bodies on Earth, as well as to determine their effects in the past as registered by the fossil record.

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Appendix A – Comparative Tables

Table 1. Energy comparisons.*

Event	Energy, J	Energy, Relative
Two 3,500-lb. cars colliding head-on at 55 mph	9.6 x 10^5	1
Explosion of 1 U.S. ton of TNT	4.2 x 10^9	4,271
Explosion of a 20-megaton fusion bomb	8.4 x 10^16	87,500,000,000
Total U.S. annual electric power production, 1990	1 x 1019	10,400,000,000,000
Energy released in last second of 10^13 kg fragment of Shoemaker-Levy 9	~ 9 x 10^21	9,375,000,000,000,000
Total energy released by 1013-kg fragment of Shoemaker-Levy 9	1.8 x 10^22	18,750,000,000,000,000
Total sunlight on Jupiter for one day	6.6 x 10^22	68,750,000,000,000,000

*1 BTU = 252 (small) calories = 1,055 J = 2.93 x 10-4 kWh.

Table 2. Power comparisons.*

Power Producer	Power, MW	Power, Relative
Hoover Dam.	1,345	1
Grand Coulee Dam, final plant.	9,700	7.2
Annual average, sum of all U.S. power plants.	320,000	238
Average, impac of 1013-kg fragment of Shoemaker-Levy 9, final sec	~ 9 x 10^15	6,700,000,000,000t

Sun	3.8 x 1020	280,000,000,000,000,000

*1 horsepower = 745.7 W = 7.457 x 10-4 MW.

Table 3. Size comparisons.*

Object	Radius, km	Volume, km^3
Jupiter	71,350 (Equatorial) 67,310 (Polar)	1.4 x 10^15
Earth	6,378 (Equatorial) 6,357 (Polar)	1.1 x 10^12
Comet Shoemaker-Levy 9	4.5 (Equivalent sphere)	382
Comet Halley	7.65 x 3.60 x 3.61	365

*1 mi. = 1.609 km

Table 4. Brightness comparisons.

Object	Magnitude Vo	Relative Brightness
Largest fragment of Shoemaker-Levy 9 during last second	~ -10	1,000
Jupiter	-2.5	1
Ganymede	4.6	1/692
Io	5.0	1/1,000
Largest fragment of Shoemaker-Levy 9 as viewed today	23.7	1/30,000,000,000

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Appendix B – The K–T Event

Sixty–five million years ago about 70% of all species then living on Earth disappeared within a very short period. The disappearances included the last of the great dinosaurs. Paleontologists speculated and theorized for many years about what could have caused this mass extinction, known as the K–T event (Cretaceous–Tertiary Mass Extinction event). Then in 1980 Alvarez, Alvarez, Asaro, and Michel reported their discovery that the peculiar sedimentary clay layer that was laid down at the time of the extinction showed an enormous amount of the rare element iridium. First seen in the layer near Gubbio, Italy, the same enhancement was soon discovered to be worldwide in that one particular 1–cm (0.4–in.) layer, both on land and at sea. The Alvarez team suggested that the enhancement was the product of a huge asteroid impact.

On Earth most of the iridium and a number of other rare elements such as platinum, osmium, ruthenium, rhodium, and palladium are believed to have been carried down into Earth's core, along with much of the iron, when Earth was largely molten. Primitive *chondritic* meteorites (and presumably their asteroidal parents) still have the primordial solar system abundances of these elements. A chondritic asteroid 10 km (6 mi.) in diameter would contain enough iridium to account for the worldwide clay layer enhancement. This enhancement appears to hold for the other elements mentioned as well.

Since the original discovery many other pieces of evidence have come to light that strongly support the impact theory. The high temperatures generated by the impact would have caused enormous fires, and indeed soot is found in the boundary clays. A physically altered form of the mineral quartz that can only be formed by the very high pressures associated with impacts has been found in the K–T layer.

Geologists who preferred other explanations for the K–T event said, show us the crater. In 1990 a cosmochemist named Alan Hildebrand became aware of geophysical data taken 10 years earlier by geophysicists looking for oil in the Yucatan region of Mexico. There a 180–km (112–mi.) diameter ring structure called *Chicxulub* seemed to fit what would be expected from a 65–million–year–old impact, and further studies have largely served to confirm its impact origin. The Chicxulub crater has been age dated (by the 40Ar/39Ar method) at 65 million years! Such an impact would cause enormous tidal waves, and evidence of just such waves at about that time has been found all around the Gulf of Mexico. Similarly, glassy debris of appropriate age called tektites (and their decomposition products), which are produced by large impacts, have been found all around the Gulf.

One can never prove that an asteroid impact killed the dinosaurs. Many species of dinosaurs (and smaller flora and fauna) had in fact died out over the millions of years preceding the K–T event. The impact of a 10–km asteroid would most certainly have been an enormous insult to life on Earth. Locally there would have been enormous shock wave heating and fires, a tremendous earthquake, hurricane winds, and trillions of tons of debris thrown everywhere. It would have created months of darkness and cooler temperatures globally. There would have been concentrated nitric acid rains worldwide. Sulfuric acid aerosols may have cooled Earth for years. Life certainly could not have been easy for those species which did survive. Fortunately such impacts occur only about once every hundred million years.

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Appendix C – The Probability of Collisions with Earth

Most bodies in the solar system with a visible solid surface exhibit craters. On Earth we see very few because geological processes such as weathering and erosion soon destroy the obvious evidence. On bodies with no atmosphere, such as Mercury or the Moon, craters are everywhere. Without going into detail, there is strong evidence of a period of intense cratering in the solar system that ended about 3.9 billion years ago. Since that time cratering appears to have continued at a much slower and fairly uniform rate. The cause of the craters is impacts by comets and asteroids. Most asteroids follow sensibly circular orbits between the planets Mars and Jupiter, but all of these asteroids are perturbed, occasionally by each other and more regularly and dramatically by Jupiter. As a result some find themselves in orbits that cross that of Mars or even Earth. Comets on the other hand, as noted in Section 2, follow highly elongated orbits that often come close to Earth or other major bodies to begin with. These orbits are greatly affected if they come anywhere near Jupiter. Over the eons every moon and planet finds itself in the wrong place in its orbit at the wrong time, many times, and suffers the insult of a major impact.

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. The meteors in our night sky are visible evidence of bodies of this type burning up high in the atmosphere. In fact, up to a diameter of about 10 m (33 ft.) most stony meteoroids are destroyed in the atmosphere in a terminal explosion. Obviously some fragments do reach the ground, because we have stony meteorites in our museums. Such falls are known to cause property damage from time to time. On October 9, 1992, a fireball was seen streaking across the sky all the way from Kentucky to New York. A 27–lb. stony meteorite (chondrite) from the fireball fell in Peekskill, New York, punching a hole in the rear end of an automobile parked in a driveway and coming to rest in a shallow depression beneath it. Falls into a Connecticut dining room and an Alabama bedroom are other well documented incursions in this century. A 10–m body typically has the kinetic energy of about five Hiroshima fission bombs, however, and the shock wave it creates can do considerable damage even if nothing but comparatively small fragments survive to reach the ground.

Many fragments of a 10–m iron meteoroid will reach the ground. The only well studied example of such a fall in recent times took place in the Sikhote–Alin Mountains of eastern Siberia on February 12, 1947. About 150 U.S. tons of fragments reached the ground, the largest intact fragment weighing 3,839 lb. The fragments covered an area of about 1–2 km^2 (0.6–1.2 mi.^2), within which there were 102 craters greater than 1 m in diameter, the largest of them 26.5 m (87 ft), and about 100 more smaller craters. If this small iron meteorite had landed in a city, it obviously would have created quite a stir. The effect of the larger pieces would be comparable to having a supersonic auto suddenly drop in! Such an event occurs about once per decade somewhere on Earth, but most of them are never recorded, occurring at sea or in some remote region such as Antarctica. It is a fact that there is no record in modern times of any person being killed by a meteorite.

It is the falls larger than 10 m that start to become really worrisome. The 1908 Tunguska event described in Section 7 was a stony meteorite in the 100–m class. The famous meteor crater in northern Arizona, some 4,000 ft. in diameter and 600 ft. deep, was created 50,000 years ago by a nickel–iron meteorite perhaps 60 m in diameter. It probably survived nearly intact until impact, at which time it was pulverized and largely vaporized as its 6– 7 4 1016 joules of kinetic energy were rapidly dissipated. An explosion equivalent to some 15 million tons of TNT creates quite a bang! Falls of this class occur once or twice every 1,000 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. The Ries Crater in Bavaria is a lush green basin some 25 km (15 mi.) in diameter with the city of N rdlingen in the middle. Fifteen million years ago a 1,500–m (5,000–ft.) asteroid or comet hit there, excavating more than a trillion tons of material and scattering it all over central Europe. This sort of thing happens about once every million years or so. Another step upward in size takes us to Chicxulub, described in detail in Appendix B, an event that occurs once in 50–100 million years. Chicxulub is the largest crater known which seems definitely to have an impact origin, but there are a few ring–like structures that are 2–3 times larger yet about which geologists are suspicious.

There are now more than 150 asteroids known that come nearer to the Sun than the outermost point of Earth's orbit. These range in diameter from a few meters to about 8 km. A working group chaired by D. Morrison estimates that there are some 2,100 such asteroids larger than 1 km and perhaps 320,000 larger than 100 m, the size that caused the Tunguska event and the Arizona meteor crater. An impact by one of the latter in the wrong place would be a great catastrophe, but it would not threaten civilization. An impact by an 8–km object is in the mass extinction category. In addition there are many comets in the 1–10–km class, 15 of them in short– period orbits that pass inside Earth's orbit, and an unknown number of long–period comets. Virtually any short–period comet among the 100 or so not currently coming near to Earth could become dangerous after a close passage by Jupiter.

This all sounds pretty scary. However, as noted earlier, no human in the past 1,000 years is known to have been killed by a meteorite or by the effects of one impacting. (There are ancient Chinese records of such deaths.) An individual's chance of being killed by a meteorite is ridiculously small as compared to death by lightning, volcanism, earthquake, or hurricane, to say nothing of the multitude of human–aided events. That small probability was unlikely to have been any consolation to the dinosaurs, however. For this reason astronomers today are conducting ever–increasing searches for all of the larger asteroids that could become dangerous. Once discovered, with a few years of warning, there is every reason to believe that a space mission could be mounted *to shove them aside.*

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