GALILEO:
EXPLORATION OF JUPITER'S SYSTEM
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This book presents the scientific objectives of the Galileo mission to the jovian system. Topics discussed include the history of the project, our current knowledge of the system, the objectives of interrelated experiments, mission design, spacecraft, and instruments. The management, scientists, and major contractors for the project are also given.
GALILEO:
EXPLORATION OF JUPITER'S SYSTEM

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The outer solar system begins somewhere in the asteroid belt, beyond Mars. The first major outpost of this vast realm is Jupiter, the giant planet. Orbiting at a mean distance of 778 million km from the Sun, Jupiter is the largest of the Sun's family of planetary companions, having a volume approximately 1000 times that of Earth. Jupiter is not merely a single large planet, however; it is the central object and master of a complex system involving four large moons, at least twelve smaller satellites, a ring system, and a powerful magnetic field that influences an immense region of space filled with charged particles of all varieties. It is the archetype of the "miniature solar systems" common to the outer parts of our planetary system—Saturn and Uranus have comparable systems, while Neptune and Pluto possess at least satellites.

Exploration of the outer reaches of our solar system began when the Pioneer 10 spacecraft, launched in 1972, flew past Jupiter in 1973, followed by Pioneer 11 about a year later. The Pioneers' visits were followed in 1979 by the spectacular reconnaissance missions of the two Voyager spacecraft. These terrestrial emissaries, extensions of our Earth-bound senses across more than half a billion kilometers of space, revealed intriguing details about Jupiter's variegated clouds, the large satellites, and the magnetic fields and charged particles surrounding the planet. Long-standing problems were resolved or seen in a new light, many discoveries were made, and totally new questions were raised as the jovian system proved to be even more complex and its members more interrelated than we had previously suspected. Intriguing new worlds of enormous complexity were viewed closely for the first time—volcanically active Io, heavily cratered Callisto, strangely marked Ganymede, and cracked Europa. Through the eyes of Voyager, astronomers saw strange planetary surfaces unlike anything previously envisioned, except perhaps in speculative fiction. Complicated electromagnetic phenomena were encountered in the vast natural laboratory of plasmas and interacting forces that surrounds the giant planet and encompasses many of its large satellites. The jovian system revealed by these preliminary explorations suggested new dimensions of fundamental studies about planets, satellites, the interplanetary medium, and the formation of systems around stars.

But the flyby missions of the Voyagers and the earlier Pioneers could not provide the in-depth long-term measurements needed to resolve the many new questions their discoveries raised. We are still a long way from having the answers required to understand our origins and to meet a very basic human need—obtaining a credible explanation and description of the causes and effects
leading to a solar system and a planet on which life could evolve so highly that it could question its own mode of origin. All civilizations have attempted to answer that question, and of all humankind we today have the best opportunities to probe this issue. One tool that we will use to press this inquiry is a product of our highest technology and advanced scientific capabilities, Project Galileo.

Project Galileo is an innovative, challenging deep-space mission—the most complex flown by the National Aeronautics and Space Administration (NASA) since the Viking program at Mars in 1976. The Galileo spacecraft (figs. 1 and 2) consists of a probe vehicle to penetrate deep into the maelstrom of Jupiter's atmosphere and an orbiter vehicle to traverse the complex magnetosphere of the planet for many months, to observe the planet's changing cloud patterns and atmospheric structure, and to closely scrutinize the major Galilean satellites, those planet-sized worlds that have proven to be so different from the inner planets of the solar system. Project Galileo will be our first chance to make an in-depth study of the jovian system. This is an important distinction. Early deep-space probes were considered "Venus missions" or "Mars missions," but Galileo is not really planet specific—it is a comprehensive survey of the entire jovian system.

Overall project management for Galileo resides with the California Institute of Technology's Jet Propulsion Laboratory in Pasadena, California, which is building the orbiter. Ames Research Center in Mountain View, California, has responsibility for the probe, to be supplied by the Hughes Aircraft Company and the General Electric Company. In addition to the many components built by aerospace firms across the United States, the Federal Republic of Germany is constructing the orbiter’s main propulsion system, two complete scientific instruments, and major elements of several others. These are being supplied to NASA free of charge under a cooperative agreement between the United States and the Federal Republic of Germany.

This book details the scientific questions to be addressed by the Galileo mission and discusses how the Galileo spacecraft, mission design, and scientific experiments will work together to unravel the secrets of the jovian system. The first four chapters explore our knowledge of the atmospheres, satellites, and magnetosphere and detail Galileo's projected contributions. Chapters 5 to 7 give a more technical review of mission design, the spacecraft, and the science instruments. Table 1 details the science payload.

History

Project Galileo had its genesis during the mid-1970s, when space scientists and NASA mission planners were considering the next steps in outer planet exploration. By that time Pioneers 10 and 11 had flown past Jupiter, but the Voyager spacecraft had not been launched. Choosing Jupiter as the obvious next target (it is the most readily accessible of the giant planets), space scientists and mission planners realized that an advanced mission should incorporate two vital elements: a probe to descend into the atmosphere and a relatively long-lived orbiter to study the planet, its satellites, and the vast expanse of the jovian magnetosphere. Such a mission was developed by NASA and approved by Congress in 1977. Although originally called Jupiter Orbiter-Probe, the program was soon renamed Project Galileo to honor the Italian astronomer who discovered the four large satellites of Jupiter that now bear his name.

Galileo was designed to be the first American planetary mission to ride the space shuttle, a decision that subsequently proved troublesome. When development and schedule problems plagued the shuttle and upper-stage rocket during 1979-1982, the Galileo Project underwent a number of frustrating and costly delays in launch date, originally slated for January 1982. The configuration evolution caused by these delays is shown in figure 3. Now, with the shuttle operational and the development of a modified, more powerful Centaur upper-stage rocket underway, Galileo is scheduled for launch in May 1986.

Getting There

For launch, the Galileo spacecraft, orbiter plus probe, will be attached to the top of a modified Centaur rocket, the same basic hydrogen-fueled upper stage that was used for the Surveyor, Viking, Pioneer, and Voyager launches. This time, however, instead of being mounted in turn on a
larger, first-stage booster rocket, the entire spacecraft—Centaur combination will be loaded into the shuttle’s cargo bay for its trip into Earth orbit. Figure 4 shows the launch sequence. After achieving orbit, the astronauts will open the cargo bay doors and deploy the rocket and its precious payload (fig. 5). At this stage Galileo will resemble a butterfly emerging from its cocoon, with all its appendages, booms, and antennas still folded up to fit within the dimensions of the cargo bay. Once the deployment is accomplished, the shuttle will back away to a safe distance, about four nautical miles, and the Centaur’s computer will take over the launch sequence. Approximately 45 minutes after deployment, as the Centaur enters the proper “window” in space and time for injection into an interplanetary Jupiter transfer trajectory, the rocket’s computers will command the engines to ignite and Galileo will be on its way toward the giant planet.

After successful injection on its path toward Jupiter, the Galileo spacecraft will still have a series of complex steps to perform to transform itself into a functioning planetary robot. Still attached to the now spent Centaur, the spacecraft will be spun up slowly to about 0.1 rpm for stabilization, and the interplanetary “butterfly” will begin to spread its wings as its main antenna—a fine gold-plated
Orbiter
Mass = 1138 kg (includes 103 kg science payload)
Normal spin rate = 3.15 rpm
Magnetometer boom = 10.9 m
Retropropulsion module: 430-N thrust, 932 kg fuel
High-gain antenna: 4.8-m diameter, maximum data rate = 134 kilobits/s
Electric power: 570 W (at launch); 486 W (after 6 years)

Probe
Mass = 335 kg (includes 213 kg deceleration module)
Descent module: 118 kg (includes 28 kg science payload)
Probe diameter = 125 cm
Probe height = 86 cm
Heat shield: carbon phenolic nose, thickness = 10.147 mm
Data rate = 128 bits/s (Li SO, battery lifetime = 55-60 min)

Figure 2. Galileo orbiter and probe.

mesh supported by an umbrella-like structure—unfolds and the three main booms snap into place. The spacecraft will then be spun up to 3 rpm. The final step in freeing the spacecraft from Earth will occur when the metal band attaching the spacecraft to the spent rocket is fractured by an explosive ring. From that point, Galileo will be an independent entity, and the long process of checking out its various systems and functions and preparing for arrival at Jupiter will begin.

Galileo will arrive in the vicinity of Jupiter after an interplanetary transit of a little more than two years (fig. 6). Figure 7 presents a schedule of major mission events. One hundred and fifty days before its arrival at Jupiter, the probe will be separated from the orbiter and will head straight for the planet, while the orbiter will back off to fly in formation as both spacecraft drop into the jovian gravity well.

Finally, some time in late 1988, the pair will reach their destination and begin a flurry of intense activities (fig. 8). As the orbiter passes within 1000 km of the volcanic moon Io, the probe will plunge toward the swirling cloud tops girdling Jupiter’s equator. A few hours later the orbiter will reach a point 230,000 km from the planet and begin relaying to Earth precious data being radioed by the probe as it descends by parachute into the atmosphere. About an hour after the probe completes its transmission, the orbiter’s retrorocket will
burn for about 46 minutes. This firing, in combination with the gravitational effect of the close Io flyby, will ease the orbiter into a long, looping jovian orbit with a period of 200 days.

As the spacecraft recedes from Jupiter along this path, scientists will have already begun to analyze the hour-long spurt of data gathered by the probe, and our in-depth exploration of the jovian system will be truly underway. In the next 20 months, the orbiter will orbit Jupiter eleven times, making a close flyby of a Galilean satellite in each orbit, using the gravity of the satellites to adjust its flight path, and studying the planet and its rings, satellites, and magnetosphere.

**Scientific Objectives**

The entire design of the Galileo mission is dictated by the many-faceted and interrelated nature of the jovian system (appendix C and fig. 9). Subsequent chapters detail our current knowledge concerning the three major components of the system: the planet, the major satellites, and the magnetosphere. These chapters also outline some of the main questions in these areas and the advances that we hope to make with the many Galileo investigations.

Most of Galileo's science goals are underlaid by our view of Jupiter as a system that holds clues to conditions in the early solar system at the time of planet formation 4.6 billion years ago, the processes that initially modified and shaped the newly formed planetary bodies, including Earth, and the processes that are still active today, ranging from volcanic activity on Io to astrophysical plasma processes in the vast magnetosphere. Also, although most investigations can be classified as relating to atmospheric, satellite, or magnetospheric

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### Science Objectives of the Galileo Mission

**Atmosphere**

- Determine the chemical composition
- Determine the structure to a depth of at least 10 bars
- Determine the nature of the cloud particles and location and structure of cloud layers
- Determine the radiative heat balance
- Investigate the circulation and dynamics
- Investigate the upper atmosphere and ionosphere

**Satellites**

- Characterize the morphology, geology, and physical state of the surfaces
- Investigate the surface minerology and surface distribution of minerals
- Determine the gravitational and magnetic fields and dynamic properties
- Study the atmospheres, ionospheres, and extended gas clouds
- Study the magnetospheric interactions of the satellites

**Magnetosphere**

- Characterize the energy spectra, composition, and angular distribution of energetic particles throughout the magnetosphere to 150 Rₖ
- Characterize the vector magnetic fields throughout the magnetosphere to 150 Rₖ
- Characterize the plasma energy spectra, composition, and angular distribution throughout the magnetosphere, including plasma wave phenomena, to 150 Rₖ
- Investigate satellite—magnetosphere interactions
<table>
<thead>
<tr>
<th>Experiment</th>
<th>Mass (kg)</th>
<th>Range</th>
<th>Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Probe</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atmospheric Structure Instrument (ASI)</td>
<td>4</td>
<td>Temp.: 0-540 K</td>
<td>Determine temperature, pressure, density, and molecular weight as a function of altitude</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pres.: 0-28 bars</td>
<td></td>
</tr>
<tr>
<td>Neutral Mass Spectrometer (NMS)</td>
<td>11</td>
<td>Covers 1-150 AMU</td>
<td>Determine chemical composition of atmosphere</td>
</tr>
<tr>
<td>Helium Abundance Detector (HAD)</td>
<td>1</td>
<td>Accuracy: 0.1%</td>
<td>Determine relative abundance of helium</td>
</tr>
<tr>
<td>Nepelometer (NEP)</td>
<td>5</td>
<td>0.2-20-µm particles, as few as 3/cm³</td>
<td>Detect clouds and infer states of particles (liquid versus solid)</td>
</tr>
<tr>
<td>Net-Flux Radiometer (NFR)</td>
<td>3</td>
<td>6 infrared filters from 0.3 to &gt;100 µm</td>
<td>Determine ambient thermal and solar energy as a function of altitude</td>
</tr>
<tr>
<td>Lightning and Energetic Particles (LRD/EPI)</td>
<td>2</td>
<td>Fisheye lens sensors; 1 Hz-100 kHz</td>
<td>Verify the existence of lightning and measure energetic particles in inner magnetosphere</td>
</tr>
<tr>
<td><strong>Orbiter</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solid-State Imaging (SSI)</td>
<td>28</td>
<td>1500-mm, f/8.5</td>
<td>Map Galilean satellites at roughly 1-km resolution, and monitor atmospheric circulation over 20 months while in orbit around planet</td>
</tr>
<tr>
<td></td>
<td></td>
<td>800 x 800 CCD, 8 filters, 0.47⁰ field of view</td>
<td></td>
</tr>
<tr>
<td>Near-Infrared Mapping Spectrometer (NIMS)</td>
<td>18</td>
<td>0.7-5.2-µm range, 0.03-µm resolution</td>
<td>Observe Jupiter and its satellites in the infrared to study satellite surface composition, jovian atmospheric composition and temperature</td>
</tr>
<tr>
<td>Ultraviolet Spectrometer (UVS)</td>
<td>4</td>
<td>1150-4300 angstroms</td>
<td>Measure gases and aerosols in jovian atmosphere</td>
</tr>
<tr>
<td>Photopolarimeter-Radiometer (PPR)</td>
<td>5</td>
<td>Discrete visible and near-infrared bands, radiometry to &gt;42 µm</td>
<td>Determine distribution and character of atmospheric particles; compare flux of thermal radiation to incoming solar levels</td>
</tr>
<tr>
<td>Magnetometer (MAG)</td>
<td>7</td>
<td>32-16,384 gammas</td>
<td>Monitor magnetic field for strength and changes</td>
</tr>
<tr>
<td>Energetic Particle Detector (EPD)</td>
<td>9</td>
<td>Ions: 0.020-55 MeV, Electrons: 0.015-11 MeV</td>
<td>Measure high-energy electrons, protons, and heavy ions in and around jovian magnetosphere</td>
</tr>
<tr>
<td>Plasma Detector (PLS)</td>
<td>12</td>
<td>1 eV to 50 keV in 64 bands</td>
<td>Assess composition, energy, and three-dimensional distribution of low-energy electrons and ions</td>
</tr>
<tr>
<td>Plasma Wave (PWS)</td>
<td>6</td>
<td>6-31 Hz, 50 Hz-200 kHz, 0.1-5.65 MHz</td>
<td>Detect electromagnetic waves and analyze wave-particle interactions</td>
</tr>
<tr>
<td>Dust Detector (DDS)</td>
<td>4</td>
<td>10⁻¹⁸-10⁻⁴ g, 2-50 km/s</td>
<td>Measure particles' mass, velocity, and charge</td>
</tr>
<tr>
<td>Radio Science (RS): Celestial Mechanics</td>
<td>–</td>
<td>S- and X-band signals</td>
<td>Determine mass of Jupiter and its satellites (uses radio system and high-gain antenna)</td>
</tr>
<tr>
<td>Radio Science (RS): Propagation</td>
<td>–</td>
<td>S- and X-band signals</td>
<td>Measure atmospheric structure and objects' radii (uses radio system and high-gain antenna)</td>
</tr>
</tbody>
</table>
Figure 3. Configuration contrasts for the various mission designs resulting from adapting the mission to different launch modules and launch dates.
science, it should be recognized that these areas are frequently very closely related, either directly by the processes that link them or indirectly through inferences about one or more of them drawn from study of another.

Origins

At the heart of our hopes to learn more about the early solar system from study of the jovian system are the similarities and the differences between this system and the solar system as a whole. The obvious analogy between the planets orbiting the Sun and the large moons circling Jupiter was in fact one of the most important conceptual aspects of the discovery of the moons by Galileo in 1610, leading to acceptance of the Copernican Sun-centered theory. However, our modern discoveries and understanding of the system suggest that this analogy is both more profound and more complicated than a mere similarity in the appearance of the orbits of the planets and satellites. We now know that early Jupiter was in many ways Sun-like or star-like. Even now, it is composed almost entirely of hydrogen and helium under extreme temperatures and pressures. Although it was too small to achieve the critical values of temperature and pressure necessary to ignite the fusion processes that power the stars, Jupiter apparently was quite hot and luminous during a brief period in its early history and still emits about twice as much energy as it receives from the Sun, as residual heat energy still flows out of the planet's deep interior. (This was true of Saturn only to a token extent.) Since the satellites are believed to have formed some time during this period of high luminosity, their strikingly different characteristics have been explained as a function of their proximity to Jupiter, just as the inner planets are affected by their positions near the early Sun.
Figure 5. Shuttle-Centaur deployment. (Photo courtesy of General Dynamics/Convair)
There obviously are not one-to-one relationships between the processes which formed the planets and those which formed Jupiter's satellite system. Different time scales, the smaller distances involved, and the effects of the details of Jupiter's formation and early evolution may have caused profound differences in chemical and physical processes affecting the formation of the satellite system. Although we suspect that Jupiter dominated conditions in its local vicinity, many other processes occurring in the early solar nebula, such as the intense bombardment by planetesimals that is believed to have occurred about 3.5 billion years ago, also would have altered conditions around Jupiter. In spite of these inevitable complications, however, we expect to learn much about the conditions in the primitive solar nebula and the effects of various planet formation processes from a study of Jupiter's atmosphere and the satellites. In particular, we believe that the composition of Jupiter's atmosphere, its major and minor components and isotopic ratios, may tell us about the original star stuff from which all the planets formed. Our current knowledge concerning the atmospheric composition and the formation of satellites, along with some of the many investigations in these areas we expect to undertake with the Galileo mission, is discussed in chapters 2 and 3.

The Planet

In addition to giving us clues about the conditions in the early solar nebula, Jupiter's atmosphere is a major area of study in its own right. We are interested in the current state of the atmosphere, the composition of its clouds, the variation of temperature and pressure with depth, the strength of the winds, the driving forces behind its meteorology, and the characteristics of the lightning that Voyager observed flashing on the night side of the planet. Answers to these and other questions will not only tell more about Jupiter as a planet, but will also advance our understanding of the nature of all planetary atmospheres, including our own. Chapter 2 discusses the atmospheres in detail.

The Satellites

The nature of the satellites, particularly their composition, tells us many things about the conditions around Jupiter during the period of planet
formation. The satellites are also, of course, individual worlds, each with its own unique characteristics and history. As such, they provide us with a fascinating set of natural “experiments” concerning the effects of initial conditions, size, energy sources, meteorite bombardment, and tectonic processes on the way planets evolve. From volcanically active, sulfurous Io to cold, battered Callisto, the Galilean satellites provide the Galileo mission with rich material for planetologic study. Some of what we hope to learn from the satellites is discussed in chapter 3, along with studies of the other material orbiting Jupiter: small satellites, dust, and rings.

The Magnetosphere

Jupiter possesses the strongest magnetic field and most complex magnetic environment of any planet known. The magnetosphere is that huge volume of space in which the jovian field dominates the environment, excluding for the most part the effects of the outflowing solar wind. The scale of this structure is truly impressive, enclosing a volume many times larger than the Sun; if it were visible from Earth it would appear to the eye as large as the full Moon. Inside the magnetosphere we find complex structures filled with electrons, protons, and the charged ions of oxygen and sulfur. Some of these particles, particularly the oxygen and sulfur, originate at Io and are continuously injected into a doughnut-shaped region surrounding Jupiter known as the Io torus. Ions in this torus radiate immense amounts of ultraviolet energy. The energy is continually replenished by magnetospheric processes that heat the torus ions. These ions and others from the solar wind and perhaps the ionosphere of Jupiter are spread throughout the magnetosphere and are subject to various acceleration and diffusion processes. Many

Figure 8. Arrival geometry.
of these processes have been studied on a smaller scale in Earth's magnetosphere; some are unique to Jupiter; all are of great interest to scientists attempting to understand the complex interplay of magnetic forces and matter throughout the universe. Jupiter is in effect a relatively convenient laboratory of astrophysics, where once again nature will provide us with many answers if we can ask the right questions. Chapter 4 details our current understanding of magnetospheric phenomena and addresses the many investigations Galileo will carry out to further our understanding of this complex part of the jovian system.

Finally, although we have many detailed ideas about what we expect Galileo to accomplish, it should be remembered that the most exciting results from exploratory missions are frequently totally unanticipated. Galileo, with its array of sophisticated instrumentation (fig. 2) and two-year mission about Jupiter, is designed to give us excellent opportunities to investigate the unexpected.

Investigations of Opportunity

Any time we send a spacecraft out from Earth, particularly on as long as voyage as Galileo's, opportunities arise to perform science investigations not directly related to the main objectives of the mission. These opportunities usually result from the fact that the spacecraft must traverse vast reaches of interplanetary space before arriving at its destination, from the long duration of the mission, or from some fortuitous combination of spacecraft and planetary geometry. As with previous missions, Galileo will attempt to take advantage of a number of these "investigations of opportunity."

Gravity Wave Detection

One of the opportunities recognized at the time experiments were selected for Galileo is the possibility of using certain types of radio tracking data to search for gravity waves propagating through the solar system. This investigation takes advantage of the great distance of the Galileo spacecraft from Earth during most of its mission and the tremendous sensitivity of the tracking data from NASA's Deep Space Network. Gravity waves have never been unambiguously detected by physicists, although they are a necessary consequence of Einstein's theory of general relativity; the problem lies in the fact that these waves are "coupled" in an extremely weak way to ordinary matter and only very violent astrophysical events are capable of perturbing the space-time continuum sufficiently to produce waves of detectable amplitude. Events of the necessary scale, such as the collapse of massive black holes or a collision of galaxies, are believed to be relatively infrequent and thus difficult to "catch" with short-lived experiments.

Galileo's gravity radiation experiment relies on the fact that a large-amplitude gravity wave passing through the solar system will produce an anomalous doppler signal as the distance between the spacecraft and the ground station varies ever so slightly. The greater accuracy of such doppler measurements has been further enhanced on Galileo by modifications in the X-band radio receiver. Even with this improved sensitivity, Galileo will only be able to detect waves from the most violent types of astrophysical catastrophes. For example, the Galileo search could marginally detect gravitational radiation resulting from the collision of two massive black holes in the center of our own Milky Way galaxy. The chances of actually seeing such signals are regarded as very small by most experts; however, there remain tremendous uncertainties in many of the theoretical estimates of these probabilities and the amplitudes of the resulting gravity waves. If the Galileo search does detect something, it will be an event of great significance for the entire astrophysical science community, and even if the results are negative, they can be used to set new upper limits on the frequency and amplitudes of possible gravity wave phenomena as well as to refine techniques for even more sensitive experiments in the future.

Cruise Science

Any planetary spacecraft with magnetospheric instrumentation usually attempts to make measurements of the interplanetary medium, the solar magnetic field, and the solar wind structure on its way to its final destination. These measurements are useful for both continuing study of this medium and providing needed instrument performance and calibration information prior to beginning the main portion of the mission. Although not originally included as part of the Galileo mission, such measurements are now planned. This results in part from the requirements
Figure 9. Jovian system.
for calibration data and in part from the development of an agreement with the Federal Republic of Germany that provides for periodic tracking of Galileo using a German tracking station and the provision of the data records to all interested experimenters.

**Asteroid or Comet Encounters**

Since the Galileo spacecraft will cross the asteroid belt en route to Jupiter, it is not unreasonable to expect that a close flyby of one or more of the asteroids might be possible. A preliminary search for such possibilities has been carried out using computer catalogs of main-belt asteroids, comets, and Earth-crossing asteroids, about 4000 possible targets in all. From this initial search, several promising targets have been identified, including Amphitrite, an S-class asteroid. This asteroid could in principle be approached very closely by Galileo if the spacecraft’s trajectory were altered somewhat from the optimum path to Jupiter. No decision has been made about whether to make an attempt; the effects of the extra fuel expenditure on other Galileo science objectives and the cost and risk to the mission of performing such a flyby have still to be evaluated in detail. Meanwhile, further opportunities are being sought, and Galileo may well have an opportunity to take a close look at an asteroid in late 1986 or early 1987.

**Mission Design and the Orbital Tour**

While the probe's success is keyed to its ability to penetrate the jovian atmosphere, the orbiter’s success depends on its unique trajectory, which provides for unprecedented new measurements. Once captured by Jupiter’s gravity, the orbiter would repeat its initial 200-day orbit if nothing were done; this would allow several Voyager-like passes through the system before the spacecraft “died” from radiation effects or actually dropped at its low point into the atmosphere due to gravitational perturbations of the Sun. For Galileo to be utilized more effectively during its limited lifetime, the orbital period must be shortened and the spacecraft targeted to make very close flybys of the Galilean satellites.

If this had to be accomplished by rocket propulsion, the mission would be impossible—too much fuel (and weight) would be required to do the necessary maneuvers in Jupiter’s strong gravitational field. Fortunately, mission designers have found a way to fly a very demanding, complicated mission using little fuel. They will manage this trick by employing the gravity-assist technique that successfully redirected the Voyagers and other spacecraft as they swung by various planets along their routes.

In the case of Galileo, a celestial 11- or 12-cushion billiard shot will be set up, using the gravity of the massive Galilean moons to modify the orbiter’s course during each pass. This simultaneously sends the craft on toward the next encounter and provides extremely close approaches to the satellites for scientific measurements. As a result, the entire “satellite tour” can be flown so that rockets need supply only about 100 m/s of velocity change—60 times less than what would be needed without the satellites’ help!

Chapter 5 provides an in-depth look at how this complex mission is designed and how it responds to the numerous requirements placed on it by the science objectives.

**The Spacecraft and Instruments**

To accomplish the many objectives of Galileo’s jovian exploration, some new concepts in spacecraft design and instrumentation are required. Based on earlier Pioneer, Voyager, and Mariner systems, Galileo also takes advantage of the latest microcomputer electronics, improved solid-state imaging systems for both the visual and infrared portions of the spectrum, and very-high-speed entry technology for the probe.

For the orbiter, one important innovation is its “dual spin” design, with the antenna and certain instrument booms rotating about three times per minute while another instrument platform and the spacecraft’s aft portion remain fixed in inertial space. This means that the orbiter can easily accommodate both magnetospheric experiments (which perform best when rapidly swept through large angles) and telescopic remote sensing experiments (which require very accurate and stable pointing). Also, instead of utilizing a central computer as did previous planetary spacecraft, Galileo uses dozens of microcomputers scattered among its subsystems and experiments to provide unprecedented operational flexibility.

On its spinning portion, the orbiter has instruments to measure Jupiter’s magnetic field, the charged particles and plasmas trapped in the
magnetosphere, and the electromagnetic and electrostatic waves propagating through this environment. One new instrument will examine the frequency and paths of micrometeoroids near Jupiter. Investigators will use the spacecraft’s radio system to probe Jupiter’s atmosphere and to search for atmospheres on the satellites. In general, these newer instruments have greater sensitivity, energy range, and angular resolution than their Voyager counterparts.

The nonspinning portion carries four instruments on a pointable mounting boom (the scan platform) that are all new in one way or another. A photopolarimeter-radiometer will measure the polarization of light scattered from Jupiter’s clouds and the satellites’ surfaces, and its infrared channels will sound the atmosphere and measure satellite temperatures. An ultraviolet spectrometer will operate from wavelengths of 1150 to 4300 angstroms (from just below the radiation from neutral hydrogen in the Lyman-alpha band to the blue end of the visible spectrum). The near-infrared mapping spectrometer is a newly developed instrument designed to map the satellites in 200 spectral channels and discern any compositional variation across their surfaces. It will also study cloud structure and gas composition in the jovian atmosphere.

The most familiar scan-platform instrument—a TV camera—is also included. Its optical portion (actually a telescope with a focal length of 1500 mm) is a Voyager spare, but the sensor electronics are entirely new. Instead of using a conventional TV vidicon tube, Galileo’s camera has a charge-coupled device at its focal plane. The charge-coupled device is a 1 cm² silicon “chip” containing 640,000 individual diode sensors in an 800 by 800 array. It is over 100 times more sensitive than Voyager’s vidicons and can “see” out to about 9000 angstroms in the near infrared.

Galileo’s probe is similar in concept to those on the 1977 Pioneer Venus mission, incorporating experiments to measure temperature and pressure along the descent path, locate major cloud decks, and analyze the chemistry of atmospheric gases. In addition, the probe will attempt to detect and study jovian lightning both by looking for optical flashes and by listening for the radio “static” they generate. The latter detector will also measure high-energy electrons close to Jupiter just prior to atmospheric entry.

Slowing the probe as it “hits” the atmosphere presents a crucial engineering challenge. Unlike the Pioneers’ relatively low entry speed at Venus (12 km/s), the Galileo probe will be greatly accelerated by Jupiter’s immense gravitational pull and will strike the atmosphere at about 50 km/s—more than 160,000 km/hr! Its deceleration to about Mach 1—the speed of sound—should take just a few minutes and will cause a tremendous buildup of heat in the probe’s protective covering. These entry conditions, far more severe than those faced by returning Apollo astronauts, cannot be simulated in conventional wind tunnels. New facilities at NASA’s Ames Research Center were required to test heat shield materials, which make up approximately half the overall weight of the probe.

On the brighter side, once it survives its fiery entry, the probe will operate in a more benign environment than did its Pioneer predecessors. It will not have to cope with corrosive sulfuric acid clouds or the furnace-like temperatures at Venus’ surface. Jupiter’s atmosphere is primarily hydrogen and helium, of little consequence to the spacecraft or its parachute, and for most of the descent the probe will be immersed in gases at or below room temperature. Eventually, however, it will sink below the visible clouds, where rising pressure and temperature will take their toll.

More detailed information about the spacecraft design is found in chapter 6; instruments are discussed individually in chapter 7.
Jupiter is the prototype of the four “jovian planets,” grouped with Saturn, Uranus, and Neptune. Although each is unique, as a group they differ sharply from the terrestrial planets in that they are much larger but have much smaller mean densities. Mercury, Venus, Earth, Moon, and Mars can all be regarded as composed of a varying mixture of rock and iron. Similar material probably is buried in the cores of the jovian planets, but it is surrounded by huge envelopes of gas, principally hydrogen and helium. Small proportions of the hydrides of carbon, nitrogen, and oxygen [methane (CH₄), ammonia (NH₃), and water (H₂O)] are also present. All three are observed in Earth-based spectra of Jupiter, but the less volatile ones (H₂O and NH₃) disappear from view in the other, colder planets, undoubtedly because they condense to form clouds at levels too deep to be seen.

Some of these clouds are readily visible from Earth and have been studied in detail by the Voyagers (fig. 10). A wide range of meteorologic phenomena has been studied from Earth and other spacecraft and will be studied further by Galileo. Figure 11 summarizes current ideas about the clouds and deeper levels.

The term “structure” for an atmosphere refers to a description of pressure, density, and temperature as functions of height. Cloud density and composition are sometimes included. Once the composition is known, most of the other quantities can be derived from the temperature profile, along with the equation of state, represented in many cases by the ideal gas law (the relationships among temperature, pressure, and volume obeyed by an idealized gas).

The following sections correspond to the three areas discussed above: composition, meteorology, and structure. A fourth section discusses satellite atmospheres. In each area the present state of knowledge is summarized; the major open questions are then discussed, along with Galileo’s expected contributions to their solutions.

**Composition**

Early measurements of the ratios of helium (He), carbon (C), and nitrogen (N) to hydrogen (H) at Jupiter gave values close to those for the Sun and, along with the obvious rarity of rock and iron relative to gas, encouraged the view that the compositions of Jupiter and the Sun are indeed identical. The Voyager results for He are still in agreement with this concept, but current analyses of Jupiter’s methane spectrum show an overabundance of carbon compared to solar values by a factor of 2 to 3. Similar factors are derived from gravity data for the rocky core. Water, on the other
Figure 10. Observed close up, the patterns of the clouds provide much information about the complex dynamics of the jovian atmosphere.
Figure 11. Theoretical cross-section of Jupiter indicates current concepts of the structure of the interior and the atmosphere and identifies the cloud layers. The probe will drop through the cloud layers indicated in the inset.
hand, is apparently underabundant by more than a factor of 100. This molecule can be seen, however, in only a few special cloud-free regions which undoubtedly contain strong downdrafts and which would therefore be expected to have dried out. The average H₂O abundance is thus still very uncertain. The NH₃ abundance in the visible atmosphere is also greatly affected by cloud formation, and although ammonia can be detected at radio frequencies at deeper levels, the mixing ratio remains uncertain.

Theoretical studies of cloud formation in an atmosphere of solar composition predict three main cloud layers above the pressure range of 10 to 20 atmospheres (figs. 11 and 12). Near 0.6 atmosphere there should be a "cirrus" of ammonia crystals. At about 6 atmospheres, a dense cloud of water and ice is predicted, and in between these layers there may be a cloud of ammonium hydrosulfide (NH₄HS).

Important clues to the origin of a planet come from isotopic ratios, which are only very slightly affected by the planet's subsequent chemical evolution. Two such ratios have been measured for Jupiter: carbon 13 to carbon 12, which is the same as on Earth, and deuterium (heavy hydrogen) to hydrogen, which requires a rather uncertain correction in the mathematical analysis but is found to be only one-fifth the terrestrial value. Low values are also seen in other parts of the galaxy and may represent the initial ratio for the solar system. Noble (inert) gases are of even greater interest, but their isotopic ratios cannot be measured remotely from space.

A number of molecules, of which ethane (C₂H₆) is typical, are detected in the infrared. There is also a pervasive high-altitude aerosol, or smog, which darkens the whole planet in the ultraviolet. Such substances are expected to be produced from methane by the action of solar ultraviolet light. Lightning has also been suggested from time to time as an energy source for similar processes, but most scientists doubt that the strength of this source is at all competitive with direct sunlight.

A persistent mystery is the nature of the agent that colors the clouds. The yellow color may be due to phosphorus, sulfur compounds, or some unspecified organic compounds.

Generally speaking, the methods of remote sensing have reached their limits in the area of composition. Quantitative spectroscopy is frustrated by the need to allow for clouds whose structure and properties are poorly known and inhomogeneous. Little information can be obtained below the cloud level. Many constituents of great interest, especially N₂ and the noble gases, cannot be detected at all. These considerations were crucial when the Galileo mission was formulated with an entry probe as an integral part of the concept. The principal analytic instrument on the probe is a mass spectrometer. Because of the particular cosmologic importance of helium, there is another instrument,

**Figure 12.** Radiation absorption and emission processes in the jovian atmosphere. Incident sunlight is scattered by atmospheric molecules (Rayleigh scattering) and reflected by clouds. Thermal emission in the NIMS spectral range emanates from the lower clouds and atmospheric molecules. As this sunlight or thermal radiation traverses the atmosphere, absorption by the molecules produces characteristic spectral signatures.
the helium abundance detector, devoted to this one measurement. Descriptions of both instruments may be found in chapter 7.

The neutral mass spectrometer measures neutral gas species by ionizing them in an electron beam and selecting particular ion masses by a carefully tailored combination of fixed and oscillating electrical fields. The necessary high vacuum is produced by pumps within the instrument. The gas is introduced through a very small aperture or “leak” after passing through a complex, miniaturized plumbing and valving system. An approximation of the expected composition, expressed for solar abundances, is presented in tables 2 and 3. The minimum detectable mixing ratio, or fraction of gas present, is about $10^{-8}$, but may be considerably greater at some masses because of residual gas in the instrument or other ions of the same mass. The third column in the tables indicates some of these potential problems and likely remedies. For example, ammonia is very scarce at high altitudes, so molecules with which it interferes are best measured there. The instrument measures three kinds of samples: the unprocessed atmosphere, a sample with all but noble gases removed, and a sample of complex molecules from which the rest of the gas has been removed. Such molecules may therefore be measured even if their original mixing ratio was well below $10^{-8}$. In the noble gas sample, the proportions should be: helium, 1.0; neon, $1.7 \times 10^{-3}$; argon, $6.3 \times 10^{-5}$; krypton, $2 \times 10^{-8}$; xenon, 3 to $20 \times 10^{-9}$. Excellent isotopic ratios should be obtained for the three lightest gases and at least abundances for krypton and xenon.

### Table 2. Gross Atmospheric Composition

<table>
<thead>
<tr>
<th>Dominant Isotope</th>
<th>Mixing Ratio</th>
<th>Interference/Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular hydrogen</td>
<td>0.89</td>
<td></td>
</tr>
<tr>
<td>Helium</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>$1.47 \times 10^{-3}$</td>
<td></td>
</tr>
<tr>
<td>Methane</td>
<td>$0.83 \times 10^{-3}$</td>
<td>Ammonia/height dependence</td>
</tr>
<tr>
<td>Ammonia</td>
<td>$1.74 \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>Hydrogen sulfide</td>
<td>$2.83 \times 10^{-5}$</td>
<td>Hydrogen sulfide/fragmentation, purification</td>
</tr>
<tr>
<td>Argon-36</td>
<td>$1.77 \times 10^{-6}$</td>
<td></td>
</tr>
<tr>
<td>Neon-20</td>
<td>$0.66 \times 10^{-4}$</td>
<td></td>
</tr>
</tbody>
</table>

### Table 3. Less Abundant Species

<table>
<thead>
<tr>
<th>New Species</th>
<th>Interference/Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphine</td>
<td>$6 \times 10^{-7}$ Hydrogen sulfide/measure early, pattern</td>
</tr>
<tr>
<td>Hydrochloric acid</td>
<td>$6 \times 10^{-7}$ Argon, hydrogen sulfide/pattern, ionizing energy</td>
</tr>
<tr>
<td>Hydrogen fluoride</td>
<td>$6 \times 10^{-8}$ Neon, water/ionizing energy, pattern</td>
</tr>
</tbody>
</table>

### Isotope Ratios Accessible in this Range

<table>
<thead>
<tr>
<th>Ratio</th>
<th>Expected Value</th>
<th>Interference/Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>D/H</td>
<td>$1.5 \times 10^{-9}$</td>
<td></td>
</tr>
<tr>
<td>$^4$He/$^3$He</td>
<td>$1.4 \times 10^{-3}$</td>
<td>HD/ionizing energy, hydrogen removal</td>
</tr>
<tr>
<td>$^{18}$O/$^{16}$O</td>
<td>$2.1 \times 10^{-3}$</td>
<td>Ne/ionizing energy</td>
</tr>
<tr>
<td>$^{13}$C/$^{12}$C</td>
<td>$1.1 \times 10^{-2}$</td>
<td>NH$_3$/measure early</td>
</tr>
<tr>
<td>$^{15}$N/$^{14}$N</td>
<td>$3.6 \times 10^{-3}$</td>
<td></td>
</tr>
<tr>
<td>$^{22}$Ne/$^{20}$Ne</td>
<td>$1.2 \times 10^{-1}$</td>
<td>Ar/pattern, energy</td>
</tr>
<tr>
<td>$^{34}$S/$^{32}$S</td>
<td>$4.4 \times 10^{-2}$</td>
<td></td>
</tr>
<tr>
<td>$^{38}$Ar/$^{36}$Ar</td>
<td>$1.9 \times 10^{-1}$</td>
<td>H$_2$S/measure early</td>
</tr>
</tbody>
</table>

*Solutions refer to sequences of measurements and/or techniques of operating the mass spectrometer.*
The helium abundance detector is an interferometer that measures the refractive index of an atmospheric sample after trace gases have been removed. The measurement is accurate enough to give the helium mole fraction to 0.1 percent of the total, much more accurate than can be expected from a mass spectrometer.

No matter how deep it goes or how sophisticated its instruments, the probe will sample only one place on Jupiter. Instruments on the orbiter will be used to determine the context of the entry location and to relate the results to the rest of the planet. The principal tools will be images in all available passbands, near-infrared spectral maps from the near-infrared mapping spectrometer, and polarimetry by the photopolarimeter-radiometer related mainly to cloud structure. The ultraviolet spectrometer will explore the atmosphere mainly at altitudes much higher than those feasible for most of the probe measurements. Species that can be monitored with the near-infrared mapping spectrometer include ammonia, phosphine, water vapor, and germanium. Methane can be observed but is not expected to be variable, since it mixes well. Galileo will also search for molecules that so far have not been found in the jovian atmosphere.

A radio occultation will occur shortly after probe entry and Jupiter orbit insertion. The occultation will sound the atmosphere at nearly the same latitude as the probe but at a considerably different longitude. Nevertheless, these results should be extremely valuable for comparison with, and extension of, the probe data.

**Meteorology**

Jupiter is over ten times the diameter of Earth and spins about two and a half times faster. These differences are reflected in the visual appearances of the two planets. On Earth, the cloud patterns at middle latitudes are dominated by cyclonic storms, with a generally circular or spiral pattern. On Jupiter, the basic pattern is one of belts (less cloudy) and zones (more cloudy) arranged parallel to the equator (fig. 10). At a finer level of detail there are anticyclonic features, notably the Great Red Spot (fig. 13). Other local features, such as white ovals, brown barges, and white plumes, are of special interest. From these we may be able to learn much about atmospheric dynamics and cloud physics and composition. The Great Red Spot, for instance, may involve convection that brings material up from depths which are far from conditions of local thermochemical equilibrium. The equatorial plumes could be a type of cirrus anvil cloud arising from moist penetrative convection. The brown barges are holes in the clouds through which measurements can be made to relatively great depths.

The Voyager images produced a wealth of data on the horizontal flows at cloudtop level for latitudes to 60° north and south and on correlations with horizontal variations in cloud structure. Cloud-tracked winds indicate both horizontal variations in cloud structure and horizontal shear between zonal currents which appear conducive to the development of barotropic eddies. Measured eddy motions between zonal currents, if interpreted two dimensionally, appear to be able to accelerate the high-speed jetstreams observed in the atmosphere. Wave phenomena are apparent on a wide variety of length scales, from a series of equatorial plumes circling the entire planet and very large white anticyclones (thousands of kilometers across) in the middle latitudes down to periodic cloud forms with wavelengths of tens of kilometers. The most important limitation in all of the Voyager meteorologic data is, however, that they are essentially confined to one atmospheric level. This arises because Voyager’s imaging system observed over broad spectral ranges confined to the visual part of the spectrum and because the planet is completely covered with clouds.

A tremendous variety is seen in the texture of the cloud tops, and the differences are correlated with local features such as ovals and with large-scale structures such as the equatorial region jets and reversing currents. Correlations between global and local scales include the regular spacing of plume clouds in the equatorial region. The images also show that the Great Red Spot and the white ovals are anticyclonic, while the dark barges and some of the irregular features preceding and trailing the ovals are cyclonic. Voyager imaging provided an extensive descriptive catalog of the morphology of the cloud tops and correlations with local and global dynamic behavior.

Lightning on Earth is produced by charges generated and separated in cumulonimbus clouds (ice-water convective clouds initiated by vertical moist static instability). Collisions between water and ice cause some particles to become charged
positively and others to become charged negatively. Most lightning discharges in Earth's atmosphere occur within a cloud cell and neutralize tens of coulombs of charge. Cloud-to-ground lightning transfers negative charge from the bottom of the cloud to Earth's surface.

A similar dynamic regime may exist on Jupiter and may be responsible for the lightning detected by Voyager (figs. 14 and 15). That lightning does occur on Jupiter implies that vertical instabilities occur, and this has important implications for the large-scale atmospheric dynamics at the levels where the flashes occur. Questions now concern the frequency and global distribution of the lightning flashes and the sizes of individual storms and their locations. More details will be furnished by the lightning and radio emission detector on the probe. The range of detection by this instrument is estimated to be about 10 000 km from the probe's entry point. The data will be obtained during the entire descent of the probe, below the jovian ionosphere, and inside and below dense cloud
systems. The lightning and radio emission detector will provide information about the radio frequency noise spectrum, and will record statistics on the pulse amplitudes, widths, spacing, and shapes. The number and location of the lightning cells, the scale size of the cloud turbulence, and evidence for precipitation can then be deduced. Comparisons with terrestrial lightning characteristics will provide information about the energy content of the jovian lightning discharges.

Virtually all current results that pertain to horizontal winds are strictly two dimensional in nature. However, atmospheric dynamics depend on vertical differences in physical and chemical properties of the atmosphere and on the full three-dimensional patterns of fluid motion that compensate any imbalance of energy, particularly from equator to pole and from interior to exterior. An important contribution of Galileo imaging will be to probe the critical third dimension of Jupiter's static and dynamic structure. This will be made possible by the spectral capabilities of the new imaging device.

The Galileo camera will observe Jupiter throughout a wider range of wavelengths than possible before. Representative and special regions of Jupiter's atmosphere will be selected for detailed

![Figure 14. The Voyager spacecraft discovered lightning flashes and auroral emissions on Jupiter's night side.](image)

![Figure 15. Voyager 1 observed whistlers from lightning in the jovian atmosphere on March 5, 1979, at 5.8 R_J.](image)
study. Each region will be viewed through three or four filters every ten minutes during a period of several hours while the rotation of the planet carries the region across the face of Jupiter from morning to evening. To find out how the observed motions and inferred vertical structure change over long periods, the sequence will be repeated six or seven hours later, when the same region can be viewed again from the spacecraft. These picture sequences will be made when the spacecraft is close to Jupiter on the sunlit side, and they will resolve features as small as 30 km across. They will also be used to produce short color movies so that the motions can be readily appreciated and studied.

By using the different camera filters, we will be able to identify distinct cloud layers below the visible cloud tops. For example, the response of the charge-coupled device to near-infrared radiation (less than 10,000 angstroms) makes it possible to obtain images in spectral “windows” where absorptions due to methane modify the effective altitude being imaged. Photographs in the strongest methane band at 8900 angstroms will provide details of the atmosphere at a level above the widespread ammonia clouds. Those taken at the weaker 7250-angstrom band will show ammonia cloud features and permit observations between the clouds to levels at which the jovian atmosphere is at a higher pressure than Earth’s atmosphere at sea level. In other regions of the visible spectrum, the camera will record light reflected from still greater depths, providing there are breaks in the cloud cover. By comparing pictures of the same region photographed at different wavelengths and from different geometries, we should be able to piece together the scale height of Jupiter’s atmosphere—a three-dimensional view of the atmosphere involving the relationship between density and temperature at a scale of resolution that is of fundamental significance in the dynamics of the jovian atmosphere.

Jupiter’s atmosphere is driven by temperature differences that arise from a combination of absorbed sunlight and heat that percolates upward from the inner regions of the planet. The local energy input from the Sun can be determined by measuring the reflectivity of the jovian cloud systems and their distribution around the planet. Since it is known how much sunlight is striking the planet, a good measure of the amount of reflected light, combined with the photopolarimeter-radiometer’s measurement of the thermally emitted radiation, can determine the planetary energy budget. The reflected light can be measured by both the photopolarimeter and the charge-coupled device.

To understand the planet’s meteorology, atmospheric scientists need a comprehensive, synoptic view of Jupiter’s general circulation at high spatial resolution. In principle, Galileo could serve as a weather satellite of Jupiter to provide this synoptic view. It will systematically take pictures at several wavelengths throughout the 20-month tour and for whatever extended time may be available afterward. Such pictures will provide a wealth of information for studying the full range of dynamic phenomena that characterizes Jupiter’s atmosphere. Atmospheric processes on a variety of scales, ranging from the huge belts, zones, and spots down to features only 10 or 20 km across (fig. 16), may participate in changes on time scales ranging from minutes to centuries. Telescopic views from Earth provide data on only the largest features. The Space Telescope will sample Jupiter at smaller spatial scales (approximately 240 km across), but it may not always be scheduled with the frequency needed to provide data about events taking place relatively quickly and that are known to be important to our understanding of the jovian atmosphere. Galileo could provide such data down to very small spatial scales and over times extending from minutes to years. Galileo’s remote sensing instruments will provide complementary coverage. Figure 17 shows the relative sizes and shapes of the fields of view of these instruments.

Despite constraints placed on the use of the camera and the spacecraft by other mission requirements, Galileo will observe Jupiter for extended periods throughout the mission and will gather as much synoptic data as possible. Occasionally, maps of the cloud features will be produced at moderately high spatial resolution for comparison with data of the same region obtained by other instruments. Special attention will be paid to particular features of unusual shape or behavior. The Great Red Spot, dark barges, plumes, circulating currents, shear regions, and other known phenomena of interest will be studied using the vertical structure sequences.

All the pictures taken during the mission will be pieced together in an attempt to understand the dynamic modes through which Jupiter’s energy is
redistributed within the atmospheric layers. Cyclones, anticyclones, fronts, jet streams, convective thunderstorms, and other processes are active in Earth's atmosphere. Some of these modes may also operate on Jupiter, but there may be others of equal or greater importance. There are fundamental questions in fluid dynamics concerning the interactions of these modes, the manner in which they are manifested, and the conditions necessary for their development.

Convective motions are of particular interest because of their role in the cyclonic features. However, these studies may be hampered for several reasons. For example, if the vertical shear is strong enough, instabilities that appear as organized roll patterns may superficially resemble convective turbulence. In addition, convective modes are most likely to occur in the polar regions, which cannot be observed well from Galileo's equatorial orbit.

So-called baroclinic instabilities, analogous to those that form cyclones in Earth's atmosphere and draw energy from large-scale horizontal differences in temperature combined with wind shear, are widespread on Jupiter. In regions of large horizontal variations in wind velocity, these instabilities may become dominant. Attempts to understand Voyager data in terms of pre-Voyager theoretical

Figure 16. Dynamic regimes on Jupiter.
concepts have shown the partial applicability of some of the early ideas. However, Jupiter's atmospheric circulation is still not clearly understood. Galileo has many questions of dynamics to address, and we are likely to obtain the answers only by making the most refined observations of which Galileo is capable.

The Galileo experiments build substantially on the science and hardware experience gained from the Voyager missions. For example, the 1500-mm narrow-angle telescope, shutter, and filter systems of the Voyager imaging system are used with minor modifications for Galileo. The Galileo imaging experiment also includes several innovations in camera design. First, unlike Voyager, Galileo carries only one high-resolution camera. Second, Galileo's system has a hard-wired capability for data compression and for pixel summation of the video data stream. Third, and perhaps most significant, a cooled, solid-state detector replaces the slow-scan vidicons used in most earlier planetary missions. The Galileo imaging experiment will not only provide an in-depth scientific exploration of the remarkable phenomena discovered by Voyager, but will also provide opportunities for discovery of new phenomena by virtue of the properties of the new detector and by the nature of the orbiter's tour. For example, the charge-coupled device will be able to image the night side of Jupiter for lightning strokes, airglow, and meteoric fireballs. Further details on the camera system are given in chapter 7.

The near-infrared mapping spectrometer will investigate the important areas of chemical composition, atmospheric structure, nature of the clouds, energy balance, and atmospheric motions. The radiation received from the atmosphere in the spectral range of the instrument has two components—reflected solar radiation and thermal radiation from the lower atmosphere. Spectral maps obtained by the mapping spectrometer will provide information on composition, cloud properties, and thermal properties. Since the maps will be obtained over large parts of the atmosphere, the instrument will characterize atmospheric properties on a global scale. The 500-km resolution is several times better than that obtainable with Earth-based telescopes. The experiment can also study regions of the jovian spectrum that cannot be observed from Earth because of absorption by the terrestrial atmosphere.

As noted above, the probe's measurements will accurately determine the chemical composition at one location and for a short time only. However, for many atmospheric species, temporal and spatial variations are expected to be governed by meteorologic conditions. An obvious example of such variability on other planets is the distribution of water vapor in the terrestrial and martian atmospheres.

**Structure and Clouds**

Our current view of the structure of part of the atmosphere is given in figure 12, which covers a pressure range from 7 atmospheres (bars) to a few millibars; the temperature minimum is at about 100
millibars. The region above this minimum is the stratosphere, where temperatures rapidly become very uncertain. They may rise, as shown, to over 200 K or level off at 170 K. Various sources of information have gone into this temperature profile: 1 to 10 bars, radiometry from Earth; 0.1 to 1 bar, thermal infrared radiometry from Earth and Voyager; 0.01 to 1 bar, radio occultations of Pioneers and Voyagers; 1 microbar, stellar occultation observed from Earth.

The ionosphere and very high atmosphere have also been measured by radio occultation and by occultation (or eclipse) of the Sun observed by the Voyager ultraviolet spectrometer. In these upper regions the temperature rises steeply to a variable value, typically around 1000 K.

The cloud structure is considerably more uncertain, and the heights of the cloud layers rest mainly on theory—they are predicted to lie at the temperature levels where their assumed constituents are expected to condense.

Ground-based observations of infrared radiation from Jupiter at wavelengths of 5 \( \mu \text{m} \) indicate that there are holes in the upper cloud layer through which radiation can emerge from hot regions deeper in the atmosphere. The belts appear to be warmer than the zones and features such as the Great Red Spot. The hottest features observed are associated with blue-gray areas in the North Equatorial Belt. For an area near the center of the disk, including the Equatorial Region and the North and South Equatorial Belts, the 5-\( \mu \text{m} \) brightness exhibits a strong peak at a temperature of 250 K and two weaker ones at temperatures of 225 and 200 K. This suggests emissions from distinct layers in the atmosphere. If absorption and reemission above the radiating levels are taken into account, the temperatures of the three radiating levels, evidenced by the 5-\( \mu \text{m} \) peaks, are calculated as 292, 225, and 140 K, approximately. The visual appearance of the regions supports these calculations; namely, blue corresponds to no clouds, brown corresponds to clouds at 225 K, and white corresponds to clouds at 140 K overlying clouds at 225 K. However, other models of cloud layering could also fit the 5-\( \mu \text{m} \) data, and the Galileo orbiter’s remote sensing instruments will help unscramble the choices.

The high-altitude smog is inferred from the fact that Jupiter is rather dark in the ultraviolet, even though none of the known gases absorb ultraviolet radiation. The effect of the smog has also been seen in photometry of satellite eclipses. Similar smog is seen on Saturn and especially on Titan, where conditions are favorable for the conversion of methane to more complex hydrocarbons. The absorbed solar energy is converted to heat in the atmosphere and is responsible for the “warm” temperatures shown near the top of figure 12. Additional heating is contributed by methane absorptions in the near infrared.

For the lower, denser atmosphere there are two principal heat sources: conversion of the remaining solar energy and heat from the interior of Jupiter. The excess of emitted over absorbed energy was established by Earth-based measurements and refined by the Voyagers; it is almost a factor of 2. It is believed to be due to a remnant of the heat generated by Jupiter’s original accretion (see fig. 21). Most of the solar energy is absorbed between 1 and 3 bars. Between them, the two heat sources maintain a temperature gradient very close to the adiabatic (constant heat) value (about \(-1.9\) K/km) from levels far deeper than we can ever probe up to 1 bar or slightly less. The upper part of this region is shown by the straight line in figure 12. The upper boundary is roughly the source region for the infrared radiation to space that balances the convective heat input from below.

The atmospheric structure instrument on the probe measures temperature, pressure, and acceleration. A complete interpretation of the data requires knowledge of the mean molecular weight of the atmospheric gases, which will be derived from the mass spectrometer and supplemented at very high altitudes by the ultraviolet spectrometer. Starting at very high altitude and low density (10\(^{-14}\) g/cm\(^3\); number density, 10\(^{10}\)/cm\(^3\)) the deceleration of the probe is used as a measure of the density. With knowledge of the mean molecular weight and use of the principles of hydrostatic equilibrium, we can derive the temperature profile. The mass of the probe and heat shield must also be known; sensors in the heat shield are used to measure its rate of ablation. The upper part of figure 18 shows similar results from Pioneer Venus. Measurement of the ablation rate terminates when the velocity becomes subsonic and the parachute is opened (at Mach 1). Pressure and temperature are then measured directly, as shown for Venus in the lower part of figure 18. If the mean molecular weight is independently known, these measurements are
Figure 18. Temperature profile measured in the atmosphere of Venus by the atmospheric structure instrument on the Pioneer Venus day probe. Points indicate descent mode data. The solid line was determined from accelerations measured during high-velocity entry and extends into the lower thermosphere.

redundant and a cross-check is possible. Such experiments have demonstrated high precision and accuracy in the past, sufficient, for example, to demonstrate to meteorologists the presence on Venus of layers with subadiabatic lapse rates and on Mars of wave structure in the stratosphere.

During much of the tour, the Galileo orbits are poorly suited for use of the radio occultation technique, because the spacecraft will pass very far behind Jupiter and frequently will not be occulted at all. Even if it is, the accuracy of the results, particularly at the higher pressures, will be degraded by the large distance. Attempts will be made, however, to obtain the best structure data possible from the available occultations. Voyager data indicate considerable variability in the lower stratosphere; there is therefore no assurance that the probe measurements of this region will be representative.

The principal instrument for measuring clouds on the probe is a nephelometer, a device that sends out short flashes of light and measures the returned signal at several angles. Considerable information is therefore obtained, not only on the density of the clouds, but also on the properties of the particles (see the Venus results in fig. 19). The mass spectrometer will measure the changing composition as the vapor molecules begin to appear during penetration of a layer. If the condensate is abundant enough, the signature of its vaporization heat will appear in the temperature profile. Even if the condensate is not abundant enough to be detected by a discrete signature, the temperature at which a cloud appears is highly diagnostic of what is condensing.

The orbiter's remote sensing instruments (imaging, near-infrared mapping spectrometer, photopolarimeter, and ultraviolet spectrometer) will be used in support of the probe data. Even more important, the probe results will serve as "ground truth" or "cloud truth" to calibrate the analysis for vertical cloud structure of similar data from other parts of Jupiter. The near-infrared mapping spectrometer can also investigate the composition and vertical structure of clouds and the atmospheric temperature profile. Such work makes use of the broad spectral coverage applied to small areas of Jupiter.

The net flux radiometer on the probe will measure the difference between the upgoing and downgoing infrared fluxes. During the first part of the descent, the probe will be in late-afternoon sunlight, and the remaining solar input will be measured. At depths greater than a few bars, it is expected that only the internal heat flux will remain, but it cannot be directly measured because an increasing part of the total is carried by convection; the net flux radiometer measures only the radiative part. Several filters are used to select wavelength channels that give information on the composition, especially the crucial H₂O abundance. Little energy can be radiated through the clouds in wavelength regions that are opaque due to H₂O absorption, and the energy is forced to flow at other wavelengths. Although the precision of such a measurement is low, it should be free of systematic error and will be a valuable check on the results from the mass spectrometer.

Satellite Atmospheres

The four Galilean satellites are all massive enough to retain atmospheres, but they are undoubtedly very tenuous. Sulfur dioxide (SO₂) was
Figure 19. Signal measured in the backscatter channel of the Pioneer Venus nephelometer instrument as a function of altitude as the Venus probe descended through the atmosphere. Similar types of profiles are expected for the Galileo probe’s nephelometer experiment.

detected on Io by Voyager, and the atmosphere of Io probably contains mainly SO$_2$ and its dissociation products, including O$_2$. There is also a large and energetic plasma torus containing ions of sulfur and oxygen, as well as some neutral gas. The torus might be regarded as an extension of Io’s ionosphere but can better be treated as part of the magnetosphere (chapter 4). Europa, Ganymede, and Callisto all have water ice exposed on their surfaces and must certainly have small quantities of water vapor, as well as O$_2$, produced from it. Hydrogen escapes rapidly, and oxygen more slowly. The Voyager ultraviolet spectrometer set an upper limit to the density of Ganymede’s atmosphere in a stellar occultation; the small quantities of gas allowed by this limit are still consistent with expectations from theory. The Galileo ultraviolet spectrometer is sensitive at longer wavelengths than Voyager’s instrument and may be able to detect emissions from these thin media, stimulated by solar radiation or electron impacts.

The information about Io is much more substantial, but a considerable range of interpretations is consistent with the data. The SO$_2$ seen by Voyager could represent an atmosphere but could equally well have been from a volcanic plume. Ionospheres were detected at both limbs by radio occultation of Pioneer 10, but the samples may not have been representative. Finally, large quantities of gas must be in transit to supply the torus. On the night side, most of the SO$_2$ must freeze to the surface; if any significant atmosphere remains, it is probably O$_2$. In any case, Io’s atmosphere is probably anything but uniform. Again, the Galileo ultraviolet spectrometer may be able to detect airglow emissions that will help to tie down the atmosphere density and its day to night variation.
The jovian system is in some ways a smaller replica of the solar system. It consists of massive gaseous Jupiter with a retinue of satellites ranging from worlds the size of the terrestrial planets, down through asteroid-sized bodies, to micron-sized dust and ring particles. Although all multiple satellite systems look like small solar systems, the analogy is profoundly justified in the case of the jovian system. Jupiter, in its earliest history, was a "weak star" and created a temperature gradient in the gas cloud from which its moons formed that strongly influenced this composition and later evolution. In addition to their importance as part of a miniature solar system, several of the larger satellites have undergone extensive individual geologic evolution like that which has affected the terrestrial planets. In one case, that of Io, the intensity of geologic evolution is greater even than that which has characterized Earth.

The satellites of Jupiter fall into several groups (fig. 20): the large worlds Io, Europa, Ganymede, and Callisto and several groups of much smaller bodies. The four large regular satellites are called the Galilean satellites because they were first seen by the astronomer Galileo in 1610. Four small satellites—Adrastea, Metis, Amalthea, and Thebe—orbit Jupiter closer than Io, the innermost of the Galilean satellites. Very close to Jupiter are the orbiting particles that comprise Jupiter's faint ring system. At least two small satellites, discovered by Voyager, orbit very close to the outer edge of the ring.

The rest of Jupiter's satellites are irregular and fall into two main groups: an inner cluster that consists of small satellites (in posigrade orbits) that circle Jupiter at roughly 11.5 million km and an outer group that orbits Jupiter at roughly twice that distance. The outer satellites move in intricate retrograde orbits, making one circuit of the planet in about two years. They are so far from Jupiter that if you could stand on the surface of Amalthea you would need a small telescope to detect them. Posigrade orbits are those in which bodies revolve in the same direction as Earth in its orbit, that is, counterclockwise as viewed looking down on the north pole. Retrograde motion is oppositely directed. All the planets of the solar system revolve about the Sun in a posiggrade direction, and most also have posigrade rotation. The major exceptions to this rule are Uranus, whose axis is severely tilted, and Venus, which has retrograde rotation. However, there are numerous examples of retrograde motion among the various satellites.

The Galilean satellites are large enough to appear as measurable disks when viewed by telescope from Earth, but the largest Earth-based telescope cannot reveal details on the surfaces of any of them. All four satellites are in synchronous rotation, keeping one face turned constantly toward Jupiter, as the Moon does to Earth. These satellites
Figure 20. The satellites of Jupiter reduced to the ecliptic plane (1951 epoch) to show the four major groups—the Galilean satellites (I to IV), the inner posigrade cluster (XIII, VI, X, and VII), the outer irregular cluster (XII, XI, VIII, and IX), and the four small satellites inside the orbits of the Galilean satellites (XIV, XVI, V, and XV).
are locked in resonance in their orbits—two periods of revolution of Io about Jupiter are almost equal to one of Europa, and two of Europa are almost equal to one of Ganymede.

The Galilean satellites were first imaged from spacecraft by the Pioneers, but the low resolution did not reveal significantly greater detail than images obtained from Earth. When each of the four satellites was imaged in detail by Voyager spacecraft, however, remarkably varied levels of geologic activity were discovered.

Formational History

First we consider the importance of the satellites as members of a small-scale solar system. Our theories of the origin of the solar system, and of any other possible planetary systems, all assume that planetary bodies form from a gaseous nebula of essentially uniform composition—the material of the primordial nebula from which the Sun and all other bodies of the solar system originated about 4.6 billion years ago. As the material from which planets form condenses and the planets begin to aggregate from it, their bulk composition is determined. Terrestrial planets such as Earth were deprived of most of the light elements because those remained in the gas phase during planetary condensation, but the stronger gravitational fields of larger planets such as Jupiter were able to hold on to the light elements. A key to understanding differences among planets is how heat from a central body, such as the Sun or Jupiter, produced compositional differences among the objects that formed around it by preventing, to various degrees, the condensation of volatile compounds. Most studies of the formation of Jupiter's satellites have concluded that Io, Europa, Ganymede, and Callisto were formed by the same processes in the jovian nebula that led to the formation of planets within the primordial solar nebula. The satellite system exhibits characteristics similar to those of the solar system (fig. 21). Several billion years ago Jupiter was much hotter than it is now (fig. 22). Its fierce heat prevented condensation of ices in the inner part of the presatellite cloud, and this left the inner satellites denser than the outer satellites. Io, the innermost of the four Galilean satellites, is most dense—3.5 g/cm³. Europa, the next satellite, is also “rocky” but has an outer crust of water ice and a density of 3.04 g/cm³. Ganymede and Callisto, the outer two satellites, have densities of about 1.8 g/cm³, which suggests that they are two-thirds ice in bulk and only one-third silicate rock.

Although Jupiter never put out more than one-hundredth the heat of the present Sun (fig. 22), the satellites were profoundly affected by it because they are much closer to Jupiter than even the planet Mercury is to the Sun. For example, when Io first formed it was probably receiving as much energy from Jupiter as Earth currently receives from the Sun.

Geologic Evolution and Current State

Not only did Jupiter influence the “starting points” of the four Galilean satellites by controlling their initial composition, the planet continues to influence their subsequent evolution by pumping tidal energy into their interiors: the enormous gravitational field of Jupiter raises tides on the satellites, and tidal energy can be dissipated as heat within the satellites if these tides vary with time. The amount of heating varies dramatically among the big satellites, depending on how their orbits change due to the gravitational tugs of the other moons. Io receives the most internal heating because its interaction with Europa causes continual changes in tidal amplitude and position. Io's violent volcanic activity is driven by this energy source. In addition to contributing to Io's intense volcanism, tidal heating may sustain a liquid water ocean under the icy crust of Europa. Callisto, which receives virtually no tidal heating, has a surface much like Earth's Moon, with shoulder-to-shoulder cratering; this is evidence of bombardment from space soon after the satellite's formation and of few subsequent changes over eons of time.

Io

One of the most startling discoveries by the Voyager spacecraft was the presence of erupting sulfurous volcanoes on Io (figs. 23, 24, and 25). The huge plumes of eight geyser-like eruptions observed during the relatively brief periods of the two flybys indicate that Io is remarkably volcanic, much more so than Earth. It is seemingly the most volcanically active body of the solar system. Evidence for sulfur as a major element in Io's chemistry comes from several sources: the colors
Figure 21. The satellite system of Jupiter reflects some of the characteristics of the solar system in that the central heat source was responsible for depleting volatile gases from the inner worlds of each system.

Figure 22. During its evolution Jupiter has changed from a very hot central body to its present relatively cool condition. In the early stage of its history Jupiter emitted sufficient energy to affect the density gradient of the Galilean satellites.

are appropriate for sulfur allotropes (an allotrope is an element in two or more different forms, usually in the same phase) formed at the observed temperatures, Voyager detected gaseous sulfur dioxide (SO₂) over one volcanic area, frozen SO₂ has been identified on the surface via Earth-based telescopic spectra, and sulfur and oxygen ions dominate the surrounding magnetospheric plasma.

Voyager observed active volcanic plumes, an abundance of volcanic calderas and flows on the surface, and several hot spots. Although there are many circular volcanic caldera seen on the images
One of the most startling Voyager discoveries was the presence of volcanic eruptions on Io. Here the plume from one of the eruptions is visible on the limb of Io. Voyager detected no impact craters on this satellite. It appears that material expelled from volcanic vents and flows continually resurfaces Io. While the enormous rate of volcanic activity is well established, its precise nature is poorly understood. Particularly important are the questions of overall eruption rates and the relative roles of silicates, sulfur, and SO₂. Many of the surface features—except for the occasional mountains—may be of sulfur. However, the surface may be composed of both silicates and sulfur, with silicates providing the structural strength. Considerable uncertainty also exists concerning the relative roles of explosive volcanism, exemplified by the plumes, and quiet effusion of lava, as indicated by the numerous flows visible on the surface.

Many flows in the Voyager pictures appear to have alteration zones around their periphery. These may be caused by condensation on the surrounding terrain of volatiles such as sulfur dioxide and sulfur outgassed from the lava. Other explanations are possible, however.

There is general agreement that tidal heating is responsible for the active volcanoes on Io. The solid rocky crust may be no thicker than 20 km. While much of this crust may be made of silicates, the evidence on surface composition suggests there is an uppermost layer a few kilometers thick that is heavily enriched with elemental sulfur and sulfur compounds. However, if basaltic volcanism dominates, as has been argued by some geologists, the sulfur layer may be even thinner. The interior of Io is at least partially molten and is believed to consist of ferromagnesium silicates, with perhaps a core.
Figure 25. Pele is the largest geyser-like eruption observed in Io so far. The plume is visible above the limb of the Moon; it ascends to a height of about 300 km. Markings and flows are evidence of past eruptions. This view of Pele was made by Voyager 1; it is a mosaic produced by McEwen's technique. When Voyager 2 arrived four months after Voyager 1, Pele was inactive.

rich in iron sulfide. Perhaps elemental sulfur was produced by dissociation of iron sulfide and "floated" up to form the crust while iron sulfide and iron sank to form a core.

Io is also surrounded by a huge cloud of neutral sodium that is thought to be sputtered from its surface or atmosphere by atomic charged particles in the jovian magnetosphere. Moreover, it is highly probable that the ions of sulfur and oxygen observed throughout the entire jovian magnetosphere originate from the atmosphere or surface of Io by similar processes. Studies of the torus and neutral cloud thus have direct bearing on Io's surface composition and atmospheric processes. Calculations suggest that Io must have possessed considerable water in bulk when it formed; apparently the water was lost to space early in the satellite's history, perhaps by similar magnetospheric interactions.

Europa

The density of Europa combined with the presence of a bright icy surface indicates that it is a dominantly silicate body with a thin icy crust, perhaps up to 100 km thick. Its most distinctive geologic feature is a network of intersecting dark and light linear streaks (figs. 26 and 27). The dark streaks, which are about 10 percent darker than the surrounding terrain, are fairly straight, vary in width from about 3 to about 70 km, and are up to several thousand kilometers long. They appear to have little or no topographical relief. The light streaks are smaller than the dark ones. They appear to be ridges about 10 km wide and a few hundred meters high. They also form scallops or cusps with smooth curves that repeat regularly on a scale of one to several hundred meters.

These streaks may be surface manifestations of several tectonic processes that have deformed the ice-rich crust of this satellite. Folding in response to compression might have formed the light ridges, while fracturing in response to either compression or tension might have formed the dark streaks. The satellite has very few impact craters, which suggests a process of degradation such as viscous relaxation of an ice-rich crust or a process of surface rejuvenation such as volcanism or flooding by liquid water released from the interior through fractures.

The possibility of a liquid water ocean beneath the surface ice is plausible theoretically as well, because, although Europa receives far less tidal heat than Io, it may receive enough to keep water from freezing if it were originally liquid. Early theories of Europa's structure regard it as having a thick ice crust through which heat is transported to the surface by conduction rather than by solid-state convection. Even with radioactivity as the only heat source, these models permit liquid water to exist below 40 km. Voyager found Europa's density to be 3.03 g/cm³, which allows for the possibility of a thick ice crust. (If Europa's density had been the same as that of denser silicates, only a thin ice crust could have been considered.) The absence of large-scale topography also suggests that the crust cannot be very thin. Now, with a thick-crust model and with tidal heating thought to be much greater than radioactive heating, the chances for a liquid zone seem stronger than before.

If the cracks on Europa represent crustal expansion during freezing of a 100-km deep water shell, much more crustal expansion would be required. However, if the ice were deposited layer by layer at the base of an ice crust over a period of time, the expansion required to produce the
observed features could be obtained. In this case it is conceivable there would be no liquid zone because entrapment of the tidal heating to sustain the liquid depends, in part, on the presence of liquid in the first place.

All models proposed to explain the surface features of Europa assume that the streaks express crustal failure from stresses induced by tidal forces or by convection deeper in the interior. One theory suggests that as tidal forces slowed the spin of the satellite, the equatorial bulge relaxed and caused distinctive latitudinal variation in stress. Radial tides then became effective and formed concentric fracture patterns around those areas on Europa pointing directly toward and directly away from Jupiter. Another idea that has been considered includes the dehydration of the interior, which could have produced global expansion, with mantle convection adding a nonuniform stress. Whatever their cause (and multiple causes are thought to have produced multiple sets), these surface markings are unique among the planetary surfaces observed so far in our solar system. Closer inspection of their form and patterns is required before we can develop a clear picture of how the interior and the surface of Europa have evolved. Europa was the least studied of all the Galilean satellites because of the nature of the Voyager trajectory. It is likely that closer observation will definitely answer many of our questions about this satellite, including the exciting possibility of a crustal subsurface "ocean."

**Ganymede**

The density of Ganymede (1.93 g/cm³) suggests that this satellite is composed largely of ice. The crust can be divided into two components—dark areas of densely cratered terrain and bright bands of more sparsely cratered, grooved terrain (figs. 28 and 29). Within the latter are closely spaced, almost parallel grooves, most of which are crudely organized into long curvilinear sets but which also form equidimensional blocks or

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**Figure 26.** The intriguingly smooth surface of Europa is marred by a network of intersecting dark and light linear streaks which suggest that material from the interior continues to resurface this satellite.

**Figure 27.** Complex patterns on the icy surface of Europa may be cracks filled with dark material welling up from the interior. Very few impact craters can be seen, suggesting that active processes are still modifying Europa's surface.
Each Galilean satellite is unique. Ganymede has two distinctive surface types—old cratered terrain and grooved and modified terrain.

Fan-shaped arrays. Different sets intersect to form a variety of reticulate patterns. This grooved terrain appears to have been formed by tectonic processes that fractured and faulted the crust over a considerable period of time early in the history of the satellite, modifying or destroying the older cratered terrain. Although relatively young with respect to the darker regions, the grooved terrain is more heavily cratered than the lava plains of the Moon.

One of the major geologic questions about Ganymede concerns the origin of the grooved terrain. A former silicate-rich crust might have foundered into a water mantle, with consequent oozing of water or ice to the surface. One mechanism for this could be disruption of the lithosphere as a result of internal expansion following phase changes in the constituent ice. Another possibility is glacier-like convection in the ice-rich mantle and rafting of lithospheric blocks, analogous to the plate tectonics of Earth. Answers to these questions may possibly be obtained by mapping distribution patterns of the grooved terrain, patterns of displacements, and details of the zones of intersection between different belts of this terrain.

Another important question about Ganymede is how the viscoelastic properties of the crust evolved. The Voyager images show bright circular features with little relief in many parts of Ganymede. These features have been called palimpsests. They look like ancient craters that have merged back into the surface. Detailed observations of these features are needed to determine the deformational properties of the satellite’s crust and whether these properties have changed with time. Such information is important for studying the thermal evolution of Ganymede’s interior.

Callisto

Callisto is the most heavily cratered Galilean satellite, and it is the only body larger than 1000 km in diameter in our solar system that has not undergone extensive resurfacing since impacts molded its surface (figs. 30 and 31). Crater densities in the solar system are generally two or three times as great as those in the most heavily cratered parts of Ganymede. Callisto’s surface is clearly very ancient. Some large palimpsests are present. An extensive but degraded impact basin named Valhalla is 600 km in diameter and surrounded by closely spaced concentric rings. Clearly, Callisto’s geologic history has been more passive than that of Ganymede.

Most of the information about impact craters gathered since the beginning of the space age involves craters in silicate materials of the inner planets and the Moon. Both Ganymede and Callisto offer new opportunities to study craters in nonsilicate icy materials. The origin of central pits in craters on Ganymede and Callisto is unknown. They are probably intimately related to energy partitioning during impacts, an important matter for understanding the mechanism responsible for all kinds of cratering.

Craters on both of these large icy satellites provide clues to their thermal history. Large, old craters are very degraded; smaller, younger craters have shallow or domed floors; and small, young craters are bowl shaped. Many craters have undergone some form of degradation, depending on their age and size. The ultimate shapes of craters are probably strongly controlled by the thickness of the lithosphere of each satellite.

Ganymede and Callisto are thought to have
Plate tectonics appear to be moving crustal plates on Ganymede, but there is still evidence of meteoroid impacts. Accreted from a 2:1 mixture of water-ice and primitive meteoritic material rich in volatile gases, similar to carbonaceous chondritic meteorites. Before Voyager, we thought that internal differentiation, in which light materials floated toward the surface and dense materials sank toward the center, could have been complete for Ganymede and Callisto because of radioactive heating alone. This would have resulted in an inner rocky core and an initially convecting and liquid water mantle capped by a thin crust of ice. In these theories, differences between the thermal histories of Ganymede and Callisto caused different crustal freezing histories and hence different abilities to preserve the original mixture of silicates and ice in portions of the crust that did not melt. Also, within the lunar-sized silicate cores of these satellites, any possible assemblage of “carbonaceous-chondritic” mineral would probably have been thermally metamorphized into a higher-temperature assemblage of silicate. The icy crusts envisioned by the theorists are believed to become unstable with respect to solid-state convection and to transport heat much more rapidly than by solid-state conduction. Consequently, in these models the entire liquid mantle freezes very early in the planet’s history. This viewpoint was generally accepted before the Voyager data became available. It is still unknown whether the dark material coloring the ice is primitive carbonaceous material or whether that material fell to the center and was replaced by contaminants from meteorites and dust hitting the surface.

Although the basic theories discussed above have remained intact, the Voyager data (fig. 32) caused the differences between Ganymede and Callisto to emerge as a somewhat more intriguing problem. While the difference in density was shown to be only about 8 percent, Voyager confirmed that the difference in albedo between these two satellites arises from a much more active tectonic history on Ganymede than on Callisto. The role of tidal heating might account for the difference in the longevity of surface activity on the

**Figure 29.** Plate tectonics appear to be moving crustal plates on Ganymede, but there is still evidence of meteoroid impacts.

**Figure 30.** The outermost of the Galilean satellites, Callisto, is a heavily cratered world, which seems to indicate that its surface has not changed greatly over billions of years, in sharp contrast to the other Galilean satellites.
two satellites, since Ganymede is much closer to Jupiter than is Callisto. This heating might have extended the period during which Ganymede had a thin lithosphere and hence surface activity, but only by about 100 million years. Accretional heating differences are not great, although they also favor a more active Ganymede. If Ganymede has a much larger silicate core than Callisto, radioactive heating might account for the differences. This could stretch Ganymede's heating period to 500 million years. Coupled with tidal and accretional heating, the effect could be sufficient for Ganymede's lithosphere to express endogenic activity for 1 billion years after the lithosphere of Callisto. This would exempt the presently visible surface from the bombardment with rocky material that apparently affected the most ancient surfaces of the solar system. The grooved terrain might also have been a result of this freezing of Ganymede's mantle. The general absence of very large craters on the oldest terrain of Ganymede supports the view that Ganymede started with a liquid mantle and a solid crust no more than 10 km thick.

The small-scale topography of these objects is also a subject of considerable interest. Monostatic (using the same stationary antenna to transmit and receive) radar studies of the Galilean satellites from Earth reveal that the satellites are fundamentally different from the Moon and the terrestrial planets in terms of their radar scattering properties. Although they have very high radar reflectivities on the average, the outer three Galilean satellites do not show the strong radar return from the center of their disks that is the most prominent feature in the radar signatures of the Moon and the terrestrial planets. The surfaces of the Galilean satellites may have a basically different fine-scale structure because of the presence of ice. However, even the polar ice caps of Mars scatter radar more like the surfaces of the Moon and the terrestrial planets and unlike the Galilean satellites.

In summary, the most important issues related to the current state of the satellites include the nature of Io's volcanism and the composition of its crust; the possible existence of liquid H₂O zones in Europa, Ganymede, and Callisto; and the tectonic processes that have produced such diversity in the geologic evolution of their crusts.

Small Satellites, Rings, and Dust

Collectively, Amalthea and the recently discovered small satellites are called the inner satellites to distinguish them from the Galilean satellites (Io, Europa, Ganymede, and Callisto) and the outer satellites (J6 through J13).

The first spacecraft observations of Amalthea were made by Voyager 1 in March 1979. Essentially all of our current knowledge of the physical characteristics of Amalthea comes from a few observations made by Voyagers 1 and 2, although the satellite's approximate size and the fact that it is a very dark, red object were deduced from Earth-based observations. Amalthea is an irregular body with dimensions of 270 by 165 by 150 km. The

**Figure 31.** Concentric shock waves ripple out from the center of Callisto's Valhalla impact crater.
The satellite is not ellipsoidal in shape. The blunt end of the axis points toward Jupiter, and as far as can be determined from the Voyager data, the satellite is in synchronous rotation, as expected from dynamic theory. Its mean orbital distance is 181,300 km, and its albedo is far lower than those of the Galilean satellites, only about 0.05.

In the Voyager images of Amalthea, discrimination of surface features is limited, yet two very large craters, Pan (90 km in diameter) and Gaea (70 km in diameter), are clearly visible, and some half-dozen smaller craters are suspected. In addition to craters, ridges are evident, as is some complex, trough-like topography near the crater Pan. Local relief on the satellite reaches 20 km. Pan is at least 8 km deep, and Gaea is probably twice as deep.

Assuming a mean density of 3 g/cm³, surface gravity on Amalthea ranges from about 5 to 7 cm/s². This is roughly a factor of 5 higher than on the satellites of Mars, but approximately a factor of 20 less than on the Moon. One expects that all

**Figure 32.** Data from Voyager provided better insight into the interior and surface composition of the Galilean satellites but raised many new questions.
craters on rocky bodies the size of Amalthea will be bowl shaped. The deposition of ejecta blankets on this satellite should be intermediate between the situation on the Moon and on the satellites of Mars. Amalthea should have developed an abundant regolith—like that of the Moon, but unlike that of small asteroids—that may contain abundant, impact-generated glass.

The color and reflectance characteristics (darkness and redness) of Amalthea may be affected by the satellite's extreme environment. Prolonged exposure to charged particles in the jovian magnetosphere, contaminants such as sulfur from Io, and high-velocity micrometeoroids might combine to darken and redden Amalthea's surface material. Laboratory measurements on mixtures of carbonaceous materials with sulfur allotropes provide good (but not necessarily unique) matches to the red spectrum and low albedo of the satellite.

An inner satellite, Adrastea (1979J1), with a diameter of about 25 km, was discovered at the outer edge of Jupiter's ring. The surfaces of Adrastea and other small objects suspected to exist near the ring may well be a source for ring particles. Adrastea may also interact dynamically with the ring particles in a manner similar to that of the small satellites near the edges of Saturn's rings.

The second inner satellite, Thebe (1979J2), was discovered during analysis of Voyager photographs in the spring of 1980. A comparatively large object, it orbits at a mean distance of 3 Jupiter radii (R_J). (Jupiter's equatorial radius is 71,398 km.) Its diameter is 80 ± 10 km, and its reflectance is comparable to that of Amalthea.

The third of the inner satellites, Metis (1979J3), was discovered in the late summer of 1980 while additional images of Adrastea were being sought. This new satellite orbits close to the outer edge of the ring at a mean distance of 1.8 R_J. Its diameter is 40+ km, and its reflectance is comparable to that of Amalthea.

Both Adrastea and Metis appear to be intimately connected with Jupiter's ring. It is even possible that these two objects represent the two largest lumps of a whole spectrum of fragments. While most of the ring consists of small, micrometer-sized particles, some kilometer-sized objects could well exist but have not been detected. Continued erosion of these larger chunks may resupply the small particles needed to maintain the ring.

Three major components of the ring (fig. 33) can be identified: a bright ring with a sharp outer edge at about 1.81 R_J and a more diffuse edge at about 1.72 R_J, a faint ring extending from the inner edge of the bright ring to the surface of Jupiter, and a faint halo of material extending some 104 km above the ring plane which we believe indicates electromagnetic effects on small ring particles. All discussions of ring particles so far assume that the particles are dark like Amalthea and the inner satellites. While this assumption is reasonable, no definitive measurements exist to prove this point. Also, no definitive information concerning the color of the ring particles exists.

The environment of the inner satellites and the rings is severe. The surfaces are exposed to high doses of energetic ions, protons, and electrons in the jovian magnetosphere and high-velocity micrometeoritic bombardment, as well as probable contamination by gas and dust from Io. For instance, the surface of Amalthea is subjected to fluxes of 10^9 particles/cm^2/s of protons in the 1 to 10 MeV range. Absorption of protons and electrons by the satellite is readily apparent in the Pioneer 10 and 11 particles and fields data. However, although Pioneer did detect effects later found to be related to the rings, no particles and fields measurements directly pertinent to the inner satellites were obtained on these missions.

In addition to high doses of protons and electrons, the inner satellites are subjected to impacts by heavy ions mostly sulfur (S), oxygen (O), and sodium (Na)—diffusing away from Io. Any material injected into the inner side of the Io torus will tend to diffuse toward Jupiter and thus interact effectively with the inner satellites and the ring. Small charged dust particles may be removed from the immediate vicinity of Io by the sweeping action of Jupiter's magnetic field and eventually reach the ring. In the case of Amalthea, such material will impact the surface at 60 km/s. Uncharged micrometeoroids originating outside the jovian system will impact the surface with average velocities near 40 km/s. Thus, the spectrophotometric characteristics of the surface may have been profoundly altered by the environment. The unusual red color and low albedo of Amalthea could be the result of the high doses of electrons, protons, heavy ions, and especially of sulfur-bearing dust from Io, in which case the smaller inner satellites and the larger particles in the ring
Figure 33. This striking view of Jupiter's ring was recorded by Voyager 2 in 1979 at a distance of 1.5 million km. The unexpected brightness is probably due to forward scattering of sunlight by small ring particles. Seen within the inner edge of the brighter ring is a fainter ring which may extend all the way down to Jupiter's cloud tops.

Four optical remote sensing science instruments will be mounted aboard a steerable scan platform appended to the orbiter's despun section. They have been designed to provide complementary data.

**Imaging: Surface Geology**

The Galileo imaging experiment will lead to improved understanding of almost every aspect of jovian satellite geology. The highly successful Voyager mission revealed the geologic style of each of the satellites and raised crucial questions regarding their evolution. With Galileo we will begin systematic exploration of each of the bodies and address some of the questions raised by Voyager data. These imaging tasks will be accomplished by means of increased mission flexibility, passes 20 to 100 times closer than Voyager, a 20-month encounter sequence, and a camera with spectral resolution and range, light sensitivity, and photometric fidelity that are significantly improved over those flown on the Voyager spacecraft due to advances in the state of the art. Pertinent instrument parameters are given in chapter 7.

The special excitement of the Galileo imaging experiment derives in part from our ability to observe the changing face of Io over a period of two years, obtain our first high-resolution images of Europa, and complement Voyager's satellite coverage at even higher resolutions. Additional highlights of Galileo's imaging experiment include guidance from the results of both Voyager and prior Galileo passes; greater light sensitivity for studies of dark sides, Callisto, and the irregular satellites; better spectral resolution; and a more diagnostic spectral range reaching into the infrared. The importance of a single parameter, resolution, is worth illustrating from a qualitative point of view: resolution improvements over Voyager for Galileo result from a combination of improved encounter characteristics and camera improvements. Such resolution improvements—exceeding a factor of about 2 or 3—can result in both a quantitative change in our understanding of geologic processes and a radical qualitative change in our perception of the overall character or "physical personality" of an object. Figure 34 illustrates how enhanced resolution will aid in identifying the processes that can be inferred from morphology.

**Solid-Body Science Studies**

Among the key issues concerning Io's surface geology are the global distribution and chronology of volcanism, the styles of volcanism,
Figure 34. Both high-resolution images of specific features and lower-resolution images of broad areas are necessary to understand the "regional context" of the surface of a planetary body. These pairs of images at similar resolutions and areal coverage compare Earth with Io in an attempt to illustrate the expected resolution enhancement by the Galileo mission. Areas covered in succeeding images are outlined in the preceding images.

Earth (photo a) and Io (photo e) are shown here in relative scale to each other. In this photograph of Earth, one can study the gross structure of the surface but little can be said about the topography or geologic processes of the planet. Similarly, in the Io image, one is struck by its multicolored patches, but the boundaries between these areas are fuzzy and little can be deduced about Io's geologic processes. There seem to be no impact craters as one would normally expect to see.

In images b and f, the resolution is about 5 kilometers. On Earth (photo b), one can no longer see an entire continent. Some topographical details are visible, yet there is little information about Earth's geologic processes. In photo f, one can start to see geologic detail on Io such as volcanic calderas (left center) and mountains (lower right). (Geologic features such as these are much larger on Io than on Earth.)

Photo c is a LANDSAT image of an area of the western United States stretching from Lake Tahoe (upper left) to Lake Mead (lower right) at about 1 kilometer resolution. This resolution is comparable to the very best Voyager images of Io. It is now possible to see different types of geologic structure and to infer some of the geologic processes that are occurring in this region. Lakes, rivers, and erosional patterns can be clearly identified. The different colors of the regions indicate
that they are composed of different materials. With additional study of this image, one could determine the relative ages of the various parts of this region and could deduce its geologic history. Photo g is representative of the very best Voyager pictures of Io; only a few pictures were obtained at this resolution. This picture is typical of Galileo’s resolution for at least 50 percent of the surfaces of the Galilean satellites. Details of flow features on the flanks of Maasaw Patera are now visible, including the scarp that extends around the dark flow features. This provides information about the tectonic setting of Maasaw Patera. One can now see that in some cases color differences are superimposed on the topography, indicating that the colors are caused by a relatively thin covering of materials overlying a surface constructed by other forces.

Photo d, a LANDSAT photo of an area at the center of photo c, has a resolution of 50 meters and is typical of the very best resolution that will be obtained by Galileo. The detail in this picture allows studies of the erosional processes occurring in this region. Studies of the outwash patterns and their paths down the sides of the mountains can reveal a great deal about the sequence of geologic events. The physical state of the outwash materials (e.g., loose or consolidated) can be estimated from the topography. Differences in the color and brightnesses of the outwashed material suggest differences in the composition or particle sizes of the materials. From this, one can estimate how fast the materials were washed down from the mountains—gradually or catastrophically—and if other geologic processes redistributed these materials after they were deposited on the slopes of the mountains. Photo h must remain blank until Galileo flies by Io in 1988, but the very best resolution will be about 20 meters, allowing studies of portions of each of the Galilean satellites in images as detailed as photo d.
mineralogic and chemical changes in the composition of effused material with time, and the relationship between the bulk composition and global geophysical evolution of Io and its surface volcanism and tectonics.

Galileo's imaging experiment will make a variety of observations pertinent to these issues. Comparison of the surface conditions with what was observed by Voyager will lead directly to a better determination of eruption rates. Repeated moderate-resolution imaging observations of Io's surface will occur over a period of two years from about the orbit of Europa. New flows, as well as areas in which the former topography has been buried by plume debris, may be identified. In addition, the capability to resolve craters smaller than 100 m will place much narrower constraints on resurfacing rates than is now possible with the 1 to 5 km data. The combination of crater data (if any) and differencing (exacting comparison) with Voyager pictures may thus result in identification of areas in which volcanic activity has occurred in the eight years since Voyager, as well as areas in which little activity has occurred for millions of years. The silicate-sulfur controversy discussed earlier may be resolved partly on the basis of detailed surface morphology. The shape of lava flows depends to a large extent on the properties of the erupted lava. Detailed examination of flow dimensions, shapes, and subsidiary features such as lava channels, tubes, and levees will give an indication of the variety of eruptive styles, place constraints on lava composition, and possibly allow us to distinguish sulfur flows from silicate ones. Particularly important will be the vertical dimensions. Flow thickness depends strongly on its rheology; hence lava composition can be inferred from vertical dimensions. Caldera depths are limited by the strength of the surface materials—again by composition. Special emphasis will therefore be placed on acquiring quantitative information on topography.

Many flows appear to have alteration zones around their peripheries. These zones may be caused by condensation of volatile gases (SO$_2$, S) outgassed from the lava, but there are other possible explanations. Study of the zonal colors and their relations to the surrounding features should narrow the possibilities.

The main contribution of solid-state imaging (SSI) to understanding plume dynamics will be with respect to plume stability and scattering properties. We will be observing Io after a lapse of several years and will readily establish whether the plumes observed by Voyager are still active or whether an entirely new set has formed. We will also be able to determine from the topography and albedo markings whether other plumes formed in the interim and died out. Furthermore, by continually monitoring plume activity for two years we will determine whether activity is episodic, periodic, or continuous and on what time scale—all of which is essential for understanding plume mechanics and the overall energy dissipation system for the entire body. Much of the value of the SSI experiment will be synergistic with compositional [near-infrared mapping spectrometer (NIMS)] and radiometric (photopolarimeter-radiometer) mapping (see below). It will put that data in a morphologic context. The compositions suggested by SSI data will surely be tentative and dependent on confirmation from NIMS data. However, the imaging experiment has the best chance of isolating almost pure spectral components. Thus, it will help us understand how to begin to identify individual components from the high-resolution NIMS reflection spectra. Conversely, compositional identification with the multifilter SSI system will be backed up by the NIMS system with a 200-element infrared spectrum at a spatial resolution several times lower than that of the SSI system (discussed in the next section). The SSI experiment also has the best chance of associating compositional with morphologic boundaries; this is a key way to answer genetic questions.

Europa. Among the key questions concerning Europa's geology are the following. How many components of the prominent fracture patterns are there, and what is the chronology and genesis of each? What are the detailed characteristics of the stripes, and what are the relationships between the various surface morphologic features we might expect to see (e.g., cracks, cusps, and ridges of various ages) and their compositions? How thick is the ice crust, and what lies beneath (liquid H$_2$O? volcanically active silicate?)? Have there ever been floods of liquid H$_2$O on the surface? What is the global energy history, and how has it been affected by jovian tidal stresses or more familiar energy sources? How old is the surface, and how do the various surface areas relate to each other? Has
Europa’s surface been affected by external meteoritic and atomic particle bombardment?

Galileo imaging has the potential to resolve or at least shed additional light on the question of how Europa has evolved by:

- Adding to coverage in the polar regions to observe fracture patterns. Extensional features (e.g., graben or other depressions) would support tidal despinning models; compressional features such as ridges would support the expansion-convection model.
- Acquiring high-resolution images that would permit identification of small impact craters and so place tighter constraints on the timing of tectonic and resurfacing rates.
- Acquiring high-resolution and/or stereo images of the various streaks to provide a better definition of their morphology and sequence of formation. Such definition would place further constraints on various tectonic models and may reveal changes in style and composition of aqueous and other eruptions with time.

In summary, both the zonal structure and the surface geology on Europa are unique among the planetary objects observed so far in the solar system. Better definition of the surface morphology and distribution of compositional units will lead to improved understanding of how the interior and the surface of the satellite have evolved.

Ganymede. Among the key issues to be addressed by the imaging experiment on Ganymede is the origin of “renewed” or tectonically modified terrain (as opposed to what appears to be terrain relics from the last stages of accretional bombardment) and its relationship to the energy history of the planet.

To understand the formation mechanics of this renewed or “grooved” terrain, we must study its distribution pattern, the pattern of displacements (rift, shear, or compression together with directions), the detailed morphology of zones of interaction between different belts, and the morphology of the grooves themselves. Galileo will contribute in all of these areas by increasing the area of the planet that is covered at useful resolution and by acquiring high-resolution samples in appropriate areas.

A second question with respect to Ganymede, and one not entirely unconnected with the grooved terrain, concerns the evolution of the viscoelastic properties of the crust. In many parts of Ganymede we see palimpsests, bright circular features with little relief. These appear to be ancient craters that have undergone recovery by some form of creep. The size and age give indications of the rheologic properties of the early crust. Additional clues to the viscoelastic properties of the crust are provided by the shape of impact craters, particularly the presence and absence of central peaks and central pits, and the dimensional relations between various crater features such as depth and diameter. By analyzing data on the size and frequency distribution of palimpsests, assessing their ages by the number of superposed craters, and assembling detailed data on crater shapes and sizes of constituent features, the SSI experiment will yield a better understanding of the deformational properties of the Ganymede crust and how they have changed with time. This in turn will allow us to infer more about the thermal evolution of the interior.

Callisto. The photometric data obtained by the imaging experiment will allow comparison of the spectral reflectance of individual tiny areas on Ganymede, equal to a single picture element, with those on other objects and laboratory samples. This will allow us to answer questions such as, “Is the most pristine part of the ancient crater on Ganymede the same as terrain on Callisto?” Here the imaging must be linked with the considerably lower spatial resolution but much higher spectral resolution (and greater wavelength range) data from NIMS to form compositional maps.

The main problems to be addressed by the imaging experiment on Callisto have to do with cratering processes and the possibly primordial nature of portions of the surface and the materials on it. Much of the experimental, theoretical, and observational data on impact craters concerns silicates. High-resolution views of Callisto will provide a wealth of new data on primary shapes of craters on icy bodies, data which are essential for the theoretical and experimental modeling of such craters. Recognition of impact melt deposits in or around craters on Ganymede and Callisto would aid greatly in constraining such calculations and would serve as a point for comparison with craters on the rocky terrestrial planets. In a related area,
the origin of central pits seen in craters on Ganymede and Callisto (and parts of Mars) is unknown, although numerous hypotheses have been advanced. Because these features are probably intimately related to energy partitioning during impacts, the importance of how central pits form cannot be overemphasized—not only in terms of cratering in ice, but in the general context of impact cratering.

As on Ganymede, the crater population contains a record of the satellite's thermal history. Large old craters are palimpsests, smaller younger craters have shallow or domed floors, and small young craters are bowl-shaped. Clearly, many craters have undergone some form of recovery (return to preimpact states), and the degree of recovery depends on the age and size of the crater. Mapping the distribution of the different classes of craters may allow us to date the various stages in the development of the lithosphere and compare the timing of the like stages of Ganymede.

Since Callisto's surface is the oldest and least modified surface we have viewed in detail, the nature of the nonicy and possibly primordial material is of great interest. Since there appears to be some global physical asymmetry on Callisto, we must determine whether the nonicy material is indeed indigenous to Callisto or is merely infall. It could well be unmodified primordial material in either case. Detailed studies of photometric properties of the darkest material and its morphologic relationship to lighter material could be crucial to understanding the history of the nonicy component. Again, synergism with NIMS is apparent, with imaging providing information on the physical placement of nonicy material and the nature of the contacts with ice, while the NIMS experiment may possibly provide specific absorption band identification.

**Imaging: Bulk Composition and Internal Zonation**

Along with radio tracking, the imaging experiment will also make major contributions to our knowledge of the bulk composition, internal zonation, and physical state of the satellites. Knowledge about the size and shape of a satellite, together with its mass and gravitational moments, can provide evidence of internal differentiation or orbital evolution and constrain models of internal structure and composition.

Interesting questions include the following. Are the interiors of these satellites homogeneous or differentiated? Are they in hydrostatic equilibrium? Do they possess cores? What size? One major source of information on internal structure and physical state is the radio tracking experiment (see below). However, another major contribution comes from imaging: accurate measurements of
radii and shape should be made, and measurements of principal moments of inertia of the satellites are very important along with the tracking data to constrain models of internal structure.

Since the Galileo encounters are flybys, the quality (resolution) of the pictures will vary from region to region over the surfaces of the satellites. Thus, the accuracy of the radii measurements will vary; in some areas, however, an accuracy of 1 to 3 km should be possible. In other areas, the accuracy will drop to a few kilometers. The mean radii should be well determined and radii of the best-fit ellipsoids measured to an accuracy of a few kilometers.

**Mapping Spectrometry: Mineral Mapping and Radiometry**

To understand the chemical composition and physical state of the satellites, knowledge of the minerals or phases present on the surfaces is required, along with the distribution of such compositional units in relationship to the surface geology and morphology.

Vast differences between surface composition and bulk composition seem to be as much the rule as the exception among solar system objects. Nonetheless, our experience has shown that knowledge of surface mineral distribution and its relationship to surface geology, when combined with other information, usually provides many clues to the formational conditions and evolutionary history of the object as a whole. The classes of minerals that are known or suspected to be on the satellites include ice and frosts, various forms of sulfur and sulfides, salts, primary igneous rock-forming minerals (for example, iron-bearing silicates), products of alteration by water (clays), and possibly carbonaceous compounds. Knowledge of the mineral composition and distribution on a satellite surface provides some of the most useful evidence for studying formation history and subsequent evolution. This is so because the phases, or minerals, present reflect not only the assemblage of chemical elements incorporated into the forming satellite, but also (for example) a record of the chemical evolution of the interior reservoirs from which the materials were sequentially derived. For this reason, the Galileo payload includes the NIMS, described in chapter 7. The objective of mapping the satellite's surface mineral distribution is best served by a synergistic combination of the NIMS and imaging experiments, and the anticipation of this postencounter blending of the data has influenced the design of both of these instruments and the mission.

The Galileo NIMS investigation represents a new philosophy in remote sensing on planetary spacecraft. It combines, in one experiment, moderate to high spectroscopic and imaging capabilities (chapter 7) and utilizes the infrared region out to 5.0 \( \mu \text{m} \), which is highly diagnostic of both atmospheric and surface species. Although the experiment philosophy is new, this instrument has not required new development, being simply the marriage of a telescope with a spectrometer. This instrument capability, coupled with the orbital coverage provided by the Galileo mission, allows unique geologic investigations of the jovian satellites, along with a broad range of studies of Jupiter's atmosphere. The objectives of the infrared spectrometer experiment are to map mineral compositional units on the surfaces of the jovian satellites and to characterize the mineral content of these units.

Specifically, one can contrast the capabilities of the NIMS experiment with classic imaging experiments and pure spectroscopic investigations. For imaging experiments, as exemplified by Galileo's imaging system, one obtains a very high spatial resolving power—a factor of 25 better than the NIMS experiment—but limited spectral information. The SSI camera contains only seven spectral channels and one broadband channel. Therefore, the imaging system will be able to make high spatial resolution multispectral images, but detailed spectroscopic characterization will depend on NIMS. In contrast to the customary imaging system, previous spectral investigations have been directed toward very high spectral resolution at the expense of spatial information. Consequently, such measurements have been directed toward global properties or constrained to individual localized features.

The longest wavelength achievable by the imaging experiment is 1.1 \( \mu \text{m} \). The NIMS spectral range of 0.7 to 5.2 \( \mu \text{m} \) includes many of the spectral features of materials that might be expected to occur on the satellite surfaces. (It should be noted, however, that the NIMS spectral range was designed to overlap that of the imagery to facilitate the synergistic "blending" of data, as indicated above.) Sunlight that is reflected from the surface
shows spectral features, or absorption bands, due to molecular and lattice vibration transitions, which are often diagnostic of composition, banding, and lattice structure. Examples of some absorption bands and an example of the sharp contrast in whole-disk spectra shown by the Galileo satellites are given in figure 35. If one considers the extreme variability exhibited by these objects, it becomes clear that the type of “whole-disk” spectral information shown in the figure, although largely unambiguous, would be greatly enhanced if the composite whole-disk spectra could be broken down into these components. Recent laboratory studies also suggest that information concerning such parameters as grain size and intimacy of mixing can often be gleaned from the spectra along with the phase identification.

Regardless of detailed mineral identifications, spectral classification of compositional units and mapping of these units over the satellite surfaces are powerful tools for understanding satellite geologic processes. These studies are enhanced when compositional unit maps are combined with images and data from other scan platform experiments.

A crucial point is that Earth-based observations have already revealed many deep absorption bands on the satellites, despite the fact that only hemisphere spectra are available. This implies the possibility that when NIMS resolves the hemisphere into many thousands of spectral elements, many spectral features which are mated, suggestive, or even imperceptible in the whole-disk spectra may become exceedingly strong owing to the concentration of particular mineral components in that particular field of view. Even when operating at the highest spatial resolution, the field of view is apt to include several components. This is where imaging of the same field will be of great interpretive value for NIMS.

Thermal emission from the hot spots on Io can be used by NIMS to investigate the satellite. The warm “lakes” and calderas radiate in the infrared, and a portion of this emission occurs in the NIMS spectral range. The distribution and characteristics of these hot spots will be investigated during the Io flyby and on each subsequent orbit. The latter measurements, when obtained near perijove, will be performed at a spatial resolution of about 300 km on Io’s surface, a size comparable to some of the larger hot spots. This will be useful for understanding the energy outflow from Io and its time and space variations—especially when combined with the photopolarimeter-radiometer data (see below).

During the 20-month period of orbital operations, multiple passes of Europa, Ganymede, and Callisto will occur. With these frequent observations, NIMS will be able to map large areas of each satellite. By the end of the mission, roughly half of the surface of each of these three satellites will be spectrally mapped at a resolution of about 25 km or better. In addition, NIMS will obtain spectra of Amalthea and perhaps Jupiter’s ring and two of the outer satellites, J6 and J7.

The NIMS resolution of Io at perijove, attained repeatedly during the course of the mission, is 300 km. This means that the evolution of Io’s local or regional surface composition can be monitored with high spectral resolution by NIMS for two years and correlated with variation in thermal emission as observed by NIMS and from Earth.

**Ultraviolet Spectrometry: Atmospheric and Surface Studies**

The ultraviolet spectrometer (UVS) will identify atomic and molecular gases in the atmosphere of the satellites and their distribution in altitude and location. The UVS is sensitive to small quantities of H, O, N, C, S, N2, NO, C2, Mg, CO, SO2, N+, CO+, CO2+, and Mg++. It will identify those constituents on the surface which are ultraviolet active (e.g., SO2, NH3, O3) and obtain some information as to physical characteristics such as grain size. It will also measure plasma torus properties, including emissions from multiply ionized oxygen and sulfur as observed by Voyager.

The ability of the Galileo UVS to measure relatively small spatial domains increases the chances of finding local concentrations of ultraviolet-active substances. Already, even in whole-disk spectra, the Earth-orbital International Ultraviolet Explorer satellite has identified spectra features associated with frozen SO2 on Io and longitudinally mapped them and was able to identify features associated with implanted sulfur on Europa and torus emission features beyond the wavelength range of Voyager. The Galileo UVS will be able to map these in detail. The ability of the UVS to measure atmospheric species with good
Figure 35. Telescopic spectra of the Galilean satellites of Jupiter (upper panel) compared to laboratory measurements (lower). The full-disk spectrum of Io at the top shows an infrared absorption band at 4.1 \( \mu m \). Laboratory measurements shown below indicate that this band corresponds to sulfur dioxide (SO\(_2\)), which may occur on Io's surface as a frost or adsorbed species. The spectra of the outer Galilean satellites—Europa, Ganymede, and Callisto—show absorption features similar to the laboratory spectrum of water frost. The infrared region of the spectrum is highly diagnostic for characterization of surface materials.
vertical spatial resolution may help us to understand not only the escape rates but also the processes that have propelled the molecules into the atmosphere (e.g., thermal versus sputtering).

During the 20-month mission, the UVS will map changes in frozen and absorbed SO$_2$ coverage on Io from about 10 R$_J$ and correlate these data with variations in torus emissions and the general fields and particles environment as measured by the fields and particles instruments.

The UVS spectral coverage is from 1150 to 4300 angstroms. The addition of some 300 spectral bands in this range complements the eight charge-coupled device camera filters in the visible and nearest infrared, as well as the 200 NIMS visible and infrared bands, and virtually assures identification of any spectrally active species that is a major constituent of any spatial domain on the order of tens of kilometers. Instrument characteristics are given in chapter 7.

Photopolarimetry-Radiometry: Thermal Structures

The fourth instrument on Galileo's scan platform is the photopolarimeter-radiometer (PPR). This instrument is capable of measuring surface temperatures, heat flow, emissivity, and thermal inertia for the areas within its field of view. On a close flyby, this field of view could provide 2.5-km resolution! We will learn much about global heat flow on Io and the role of discrete sources. Also, we will investigate the crustal structure in volcanic areas via heat flow mapping to gain insights into the mechanisms of volcanism. Synoptic observations of Io made from distances near Europa's orbit over 20 months will allow correlation of both regional and global heat flow with regional and global changes in albedo, depth of absorption bands in the ultraviolet and infrared, torus ion population, and other expected regional and global variations. In addition, passive thermal measurements on all the satellites will greatly augment our understanding of the thermophysical properties and from that, the textural nature of the near-surface materials. Finally, the instrument will measure albedo and photometric functions of the material, thereby complementing compositional measurements by the NIMS, UVS, and SSI instruments.

The PPR complements the thermal measurements made by NIMS and is the only instrument on Galileo that can measure the normal thermal emission of absorbed sunlight from the Galilean satellites. Thus, the PPR is necessary for any direct measurements of surface temperature and the thermophysical properties of the surfaces.

Io and its volcanic hot spots present a special case of great scientific interest. For spots much hotter than the ambient background, measurements of thermal emission can be made by NIMS, with its higher spatial resolution and its imaging capability, as well as with the PPR. Indeed, if the spots are at a temperature of 400 K or higher, more of their energy will fall within the spectral range of NIMS than of the PPR. During the initial close flyby of Io, both instruments will do an excellent job, and together they can give a comprehensive picture of thermal radiation from hot spots over a wide spectral range. Later in the tour, when encounters take place at much greater distances, both instruments lose capability. Generally, however, NIMS remains more sensitive to hot-spot radiation than does the PPR for all encounters and spot sizes, and for the more distant encounters and the small spots, the ability of the PPR is quite limited.

Particles and Fields

Magnetometry

The study of any induced or intrinsic magnetic fields associated with the satellites will be important for our understanding of the interior structure composition and dynamics of the satellites; the way that magnetospheric particles impinge on and affect the evolution of satellite surfaces and atmospheres, including temporal variations; and fundamentals of physics of magnetic field generation in solid objects of the solar system. Along with other properties, the Galilean satellites may have global or regional magnetic fields arising from dynamo action, fossil magnetization, or electrical induction. These factors involve a key class of parameters in defining the internal intrinsic physical and chemical states of the satellites. Our understanding of the various means of creating such planetary magnetic fields is limited, since this is a relatively new area of study.

Of the three means of magnetization mentioned above, dynamo action due to self-regenerated magnetic fields arising from coupled
convective (and conducting) fluid motions and preexisting magnetic fields in planetary interiors has the longest history and is generally dealt with in the most detail. For the Galilean satellites, the possibility of such dynamo activity is mediated strongly by the exotic interior constituents thought to be present, with water (probably salty) being a possible ingredient of the interiors of at least Ganymede and Callisto. Even for Io, the density appears low for any expectation of a substantial fraction of iron, the most common high-conductivity material. Nevertheless, even subregenerative dynamo activity appears possible for these objects; this increases the likelihood that there is a global magnetic field due to dynamic processes in the interiors. Alternatively, the fact that the Moon is endowed with a spectrum of local and regional magnetic fields increases the possibility that a similar form of fossil magnetization is present on one or more of the jovian satellites. Finally, electromagnetic induction cannot be ruled out as a dynamic source of magnetic fields in the neighborhood of the Galilean satellites.

For these three main classes of field sources, fundamental constraints on the internal physical and chemical constitution prevail. In all cases, the presence of magnetic fields associated with the satellites implies strong but still poorly understood constraints on heat flux, internal thermal regimes including heat sources, and internal chemistry. Of equal interest is the effect on the neighborhood of these objects if a global magnetic field is present, for such a field will couple the planet and its atmosphere (and especially ionosphere) to the ambient jovian magnetospheric plasma.

The chances of detecting a dynamo field associated with Ganymede and Callisto may be slight. First, these objects may be frozen throughout because of the efficiency with which solid-state convection removes heat from the interiors. There is a possibility that salts may have been extensively leached from the interior, lowering the melting point. Obviously, incipient crystallization of the interior will concentrate these salts in solution. However, preliminary estimates are that only a small deep liquid zone might exist in each in equilibrium, with radiogenic heat production and loss if solid-state convection is effective in the overlying solid ice. Even if the zone were augmented, say by concentration of uranium and potassium in the liquid or by inefficiency of convection in the overlying solid, it is not clear whether a dynamo field would be detectable. This is so because, for example, sea water conductivity would probably have to be augmented by several orders of magnitude to produce an effective dynamo fluid. The question is still open, however. A detectable dynamo field on Io seems more likely because Io's interior is probably extremely hot and sustains an average surface heat flow over an order of magnitude greater than that of Earth. The high-density material we would expect to find in Io's deep material would probably be mainly FeS rather than Fe, based on chemical considerations. If so, the conductivity would be almost three orders of magnitude less than that of molten Fe. Thus, the difference would presumably have to be made up by much more vigorous convection than in the deep Earth, for example, for Io to have a strong field. Perhaps Io's enormous tidal input could satisfy this requirement. Also, the theory suggests the requirements for generating and sustaining a dynamo field are much less when the object is itself situated within a strong magnetosphere such as that of Jupiter. Finally, there is the possibility of permanent magnetization of these objects. Mercury was not expected to have a field because of its solid interior, but it does. The Moon's crust also exhibits substantial permanent paleomagnetism, as do the oceanic and continental crusts of Earth (although global properties of such rock magnetism—as opposed to specimen properties—are generally overridden by Earth's strong global field). In summary, satellite magnetic fields may be studied from Galileo and may reveal much concerning the composition, state, and dynamics of their interiors.

Plasma Experiment

The interaction between jovian magnetospheric particles and the satellites' surfaces puts satellite surface material into the magnetosphere. This material in turn is ionized and returns to the satellite surface with sufficient energy to eject still more surface material. Thus, the satellites are bombarded with their own surface material as well as with material initially derived from Jupiter or the Sun. Some satellite material is completely ejected, resulting in loss from the satellite, and some simply receives enough energy to be launched on a trajectory such that it reimpacts the satellite elsewhere. The latter can strongly affect population of the atmosphere—especially on satellites or parts of
satellites where thermal processes are relatively unimportant because of the low vapor pressure curves of the available materials or because of the low temperatures.

In steady state, there is a population of satellite-derived material around the satellites. Line emission from the Io torus can even be detected and the torus mapped from Earth. In situ orbital compositional measurements of satellite surface material is therefore possible. In principle, such plasma measurements constitute an exceedingly powerful "cross constraint" on surface compositional models, because all the other tools at our disposal on Galileo are oriented toward phase composition, with elemental composition as an indirect fallout. In contrast, the plasma measurements examine directly the elemental (ionic) composition of the plasma and only indirectly the nature of the surface phase from which it derived. The plasma instrument can measure electrons and ions from 1 eV to 50 keV, as well as identify and measure fluxes of the major species derived from satellite surfaces: Na+, K+, and S+, as well as the dominant ambient species, H+, He+, and He2+. In general, the radial

The primary specific objectives are:

- to search for evidence of "rings" of particles in jovian orbits, in addition to the ring observed by Voyagers 1 and 2.
- to search for the particles responsible for generating both the visible ring and any other rings that may be found; to determine whether the ring particles are secondary ejecta from a minor moon (or moons). If not, then a science objective will be to determine the true origin of the rings.
- to examine the hypothesis that there is a Jupiter-orbiting population of dust particles that may have derived from
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<th>Abbreviation</th>
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<tr>
<td>MLI</td>
<td>multilayer insulation</td>
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<td>MP</td>
<td>magnetopause</td>
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<td>N</td>
<td>newton</td>
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<td>NEP</td>
<td>nephelometer (probe)</td>
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<td>net flux radiometer (probe)</td>
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<td>NIMS</td>
<td>near-infrared mapping spectrometer (orbiter despun)</td>
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<td>NMS</td>
<td>neutral mass spectrometer (probe)</td>
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<td>ODM</td>
<td>orbit deflection maneuver</td>
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<td>OTM</td>
<td>orbit trim maneuver</td>
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<td>PCU</td>
<td>pyrotechnic control unit (probe)</td>
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<td>PLS</td>
<td>plasma detector (orbiter spun)</td>
</tr>
<tr>
<td>PPR</td>
<td>photopolarimeter-radiometer (orbiter despun)</td>
</tr>
<tr>
<td>PWS</td>
<td>plasma wave spectrometer (orbiter spun)</td>
</tr>
<tr>
<td>$R_e$</td>
<td>Earth radius</td>
</tr>
<tr>
<td>$R_J$</td>
<td>Jupiter radius</td>
</tr>
<tr>
<td>RAM</td>
<td>random access memory</td>
</tr>
<tr>
<td>RF</td>
<td>radio frequency</td>
</tr>
<tr>
<td>RFS</td>
<td>radio frequency subsystem (orbiter)</td>
</tr>
<tr>
<td>RHU</td>
<td>radiosotope heater unit (probe)</td>
</tr>
<tr>
<td>ROM</td>
<td>read-only memory</td>
</tr>
<tr>
<td>RPM</td>
<td>retropropulsion module (orbiter spun)</td>
</tr>
<tr>
<td>RRA</td>
<td>relay radio antenna (orbiter despun)</td>
</tr>
<tr>
<td>RRH</td>
<td>relay radio hardware (orbiter despun)</td>
</tr>
<tr>
<td>RS</td>
<td>radio science (orbiter spun)</td>
</tr>
<tr>
<td>RTG</td>
<td>radioisotope thermoelectric generator (orbiter spun)</td>
</tr>
<tr>
<td>RTI</td>
<td>real-time interrupt</td>
</tr>
<tr>
<td>rpm</td>
<td>revolutions per minute</td>
</tr>
<tr>
<td>SAS</td>
<td>scan actuator assembly</td>
</tr>
<tr>
<td>SBA</td>
<td>spin bearing assembly (orbiter)</td>
</tr>
<tr>
<td>SPIU</td>
<td>system power interface unit (probe)</td>
</tr>
<tr>
<td>SRM</td>
<td>solid rocket motor</td>
</tr>
<tr>
<td>SS</td>
<td>star scanner (orbiter spun)</td>
</tr>
<tr>
<td>SSI</td>
<td>solid-state imaging (orbiter despun)</td>
</tr>
<tr>
<td>STS</td>
<td>Space Transportation System</td>
</tr>
<tr>
<td>T</td>
<td>Tesla; time</td>
</tr>
<tr>
<td>TCM</td>
<td>trajectory correction maneuver</td>
</tr>
<tr>
<td>TWTA</td>
<td>traveling wave tube amplifiers (orbiter)</td>
</tr>
<tr>
<td>UVS</td>
<td>ultraviolet spectrometer (orbiter despun)</td>
</tr>
<tr>
<td>VEGA</td>
<td>Earth-Venus-Earth gravity assists</td>
</tr>
<tr>
<td>$\Delta V$</td>
<td>velocity change</td>
</tr>
<tr>
<td>$\Delta$-VEGA</td>
<td>Earth-deep space $\Delta V$-Earth gravity assists</td>
</tr>
</tbody>
</table>
Appendix C.
Characteristics of Jupiter and the Jovian System

Characteristics of Jupiter, Earth, and Moon

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Jupiter</th>
<th>Earth</th>
<th>Moon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reciprocal mass</td>
<td>1,047.355</td>
<td>328,900</td>
<td>27,069,000</td>
</tr>
<tr>
<td>Mass (Earth = 1)</td>
<td>317.893</td>
<td>1.0000</td>
<td>0.01230</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>1.900 x 10^{27}</td>
<td>5.975 x 10^{24}</td>
<td>7.350 x 10^{22}</td>
</tr>
<tr>
<td>Equatorial radius (Earth = 1)</td>
<td>11.27</td>
<td>1.00</td>
<td>0.2725</td>
</tr>
<tr>
<td>Equatorial radius (km)</td>
<td>71,398</td>
<td>6,378</td>
<td>1,738</td>
</tr>
<tr>
<td>Ellipticity</td>
<td>0.0637</td>
<td>0.0034</td>
<td>0.002</td>
</tr>
<tr>
<td>Mean density (g/cm^3)</td>
<td>1.314</td>
<td>5.52</td>
<td>3.34</td>
</tr>
<tr>
<td>Equatorial surface gravity (m/s^2)</td>
<td>22.88</td>
<td>9.78</td>
<td>1.62</td>
</tr>
<tr>
<td>Equatorial escape velocity (km/s)</td>
<td>59.5</td>
<td>11.2</td>
<td>2.38</td>
</tr>
<tr>
<td>Sidereal rotation period</td>
<td>9.841 hours (\equiv)</td>
<td>23,945 hours</td>
<td>322 days</td>
</tr>
<tr>
<td>Inclination of equator to orbit</td>
<td>3(^{\circ}).08</td>
<td>23(^{\circ}).44</td>
<td>6(^{\circ}).68</td>
</tr>
</tbody>
</table>

Characteristics of Planetary Orbits

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>(AU)</th>
<th>(10^6 km)</th>
<th>Sidereal period (years)</th>
<th>Synodic period (days)</th>
<th>Mean orbital velocity (km/s)</th>
<th>Eccentricity</th>
<th>Inclination to the ecliptic (degrees)</th>
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</thead>
<tbody>
<tr>
<td>Earth</td>
<td>1.0000000</td>
<td>149.6</td>
<td>365.256</td>
<td>---</td>
<td>29.79</td>
<td>0.0167</td>
<td>---</td>
</tr>
<tr>
<td>Jupiter</td>
<td>5.20256</td>
<td>778.3</td>
<td>11.8623</td>
<td>4332.71</td>
<td>13.06</td>
<td>0.0485</td>
<td>1.30</td>
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</table>

Satellites of Jupiter

<table>
<thead>
<tr>
<th>Number</th>
<th>Name</th>
<th>Discoverer</th>
<th>Year of discovery</th>
<th>Mean distance from Jupiter (km)</th>
<th>Sidereal period (days)</th>
<th>Orbital inclination (degrees)</th>
<th>Orbital eccentricity</th>
<th>Radius (km)</th>
<th>Mass (kg)</th>
<th>Mean density (g/cm^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1</td>
<td>Io</td>
<td>S. Synnott</td>
<td>1979-1980</td>
<td>127,960</td>
<td>0.295</td>
<td>0</td>
<td>0.013</td>
<td>55.7</td>
<td>120.8</td>
<td>0.026</td>
</tr>
<tr>
<td>J2</td>
<td>Europa</td>
<td>S. Marius</td>
<td>1960</td>
<td>670,900</td>
<td>3.551</td>
<td>0.47</td>
<td>0.009</td>
<td>1569</td>
<td>4.873</td>
<td>0.017</td>
</tr>
<tr>
<td>J3</td>
<td>Ganymede</td>
<td>S. Marius</td>
<td>1960</td>
<td>1,070,000</td>
<td>7.155</td>
<td>0.21</td>
<td>0.002</td>
<td>2631</td>
<td>1.490</td>
<td>0.013</td>
</tr>
<tr>
<td>J4</td>
<td>Callisto</td>
<td>S. Marius</td>
<td>1960</td>
<td>1,880,000</td>
<td>16.689</td>
<td>0.51</td>
<td>0.007</td>
<td>2400</td>
<td>1.064</td>
<td>0.013</td>
</tr>
<tr>
<td>J5</td>
<td>(Metis)</td>
<td>S. Synnott</td>
<td>1979</td>
<td>128,980</td>
<td>0.298</td>
<td>0</td>
<td>0.013</td>
<td>55.7</td>
<td>120.8</td>
<td>0.026</td>
</tr>
<tr>
<td>J6</td>
<td>(Adrastea)</td>
<td>D. Jewitt</td>
<td>1979</td>
<td>128,980</td>
<td>0.298</td>
<td>0</td>
<td>0.013</td>
<td>55.7</td>
<td>120.8</td>
<td>0.026</td>
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<tr>
<td>J7</td>
<td>Amalthea</td>
<td>E. Barnard</td>
<td>1892</td>
<td>181,300</td>
<td>0.498</td>
<td>0.45</td>
<td>0.003</td>
<td>135.85</td>
<td>73</td>
<td>?</td>
</tr>
<tr>
<td>J8</td>
<td>Thebe</td>
<td>S. Synnott</td>
<td>1979-1980</td>
<td>221,900</td>
<td>0.675</td>
<td>(0.9)</td>
<td>0.013</td>
<td>55.7</td>
<td>120.8</td>
<td>0.026</td>
</tr>
<tr>
<td>J9</td>
<td>Io</td>
<td>S. Marius</td>
<td>1960</td>
<td>670,900</td>
<td>3.551</td>
<td>0.47</td>
<td>0.009</td>
<td>1569</td>
<td>4.873</td>
<td>0.017</td>
</tr>
<tr>
<td>J10</td>
<td>Europa</td>
<td>S. Marius</td>
<td>1960</td>
<td>1,070,000</td>
<td>7.155</td>
<td>0.21</td>
<td>0.002</td>
<td>2631</td>
<td>1.490</td>
<td>0.013</td>
</tr>
<tr>
<td>J11</td>
<td>Ganymede</td>
<td>S. Marius</td>
<td>1960</td>
<td>1,880,000</td>
<td>16.689</td>
<td>0.51</td>
<td>0.007</td>
<td>2400</td>
<td>1.064</td>
<td>0.013</td>
</tr>
<tr>
<td>J12</td>
<td>Callisto</td>
<td>S. Marius</td>
<td>1960</td>
<td>1,880,000</td>
<td>16.689</td>
<td>0.51</td>
<td>0.007</td>
<td>2400</td>
<td>1.064</td>
<td>0.013</td>
</tr>
<tr>
<td>J13</td>
<td>Leda</td>
<td>C. Kowal</td>
<td>1974</td>
<td>11,094,000</td>
<td>238.7</td>
<td>26.1</td>
<td>0.148</td>
<td>(5)</td>
<td>?</td>
<td>?</td>
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<tr>
<td>J14</td>
<td>Himalia</td>
<td>C. D. Perrine</td>
<td>1904-1905</td>
<td>11,480,000</td>
<td>250.6</td>
<td>27.6</td>
<td>0.158</td>
<td>(90)</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>J15</td>
<td>Lysithea</td>
<td>S. B. Nicholson</td>
<td>1938</td>
<td>11,720,000</td>
<td>259.2</td>
<td>29.0</td>
<td>0.107</td>
<td>(10)</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>J16</td>
<td>Elara</td>
<td>C. D. Perrine</td>
<td>1904-1905</td>
<td>11,737,000</td>
<td>259.7</td>
<td>24.8</td>
<td>0.207</td>
<td>(40)</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>J17</td>
<td>Ananke</td>
<td>S. B. Nicholson</td>
<td>1951</td>
<td>21,200,000</td>
<td>631</td>
<td>147</td>
<td>0.17</td>
<td>(10)</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>J18</td>
<td>Carne</td>
<td>S. B. Nicholson</td>
<td>1918</td>
<td>22,600,000</td>
<td>692</td>
<td>164</td>
<td>0.21</td>
<td>(15)</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>J19</td>
<td>Pasiphae</td>
<td>P. Mellote</td>
<td>1908</td>
<td>23,500,000</td>
<td>735</td>
<td>145</td>
<td>0.38</td>
<td>(20)</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>J20</td>
<td>Sinope</td>
<td>S. B. Nicholson</td>
<td>1914</td>
<td>23,700,000</td>
<td>758</td>
<td>153</td>
<td>0.28</td>
<td>(15)</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>


Parenthetical names and satellite numbers await approval by the International Astronomical Union. Parenthetical values are uncertain by at least 10 percent. Inclinations and eccentricities are the total values; "forced" components are important for the eccentricities of the satellites Io and Europa. Inclinations are with respect to planetary equators for inner satellites and to orbital planes for outer ones. Compound radii are the values for the "best-fit" triaxial ellipsoid.

1The mass of the Sun divided by the mass of the planet (including its atmosphere and satellites). 2Satellite masses not included. 3The ellipticity is \(R_e - R_p\). \(R_e\) and \(R_p\) are the planet's equatorial and polar radii. 4Jupiter's internal (System III) rotation period is 9.925 hours. 5At equator.
References


