15

Galilean Satellites: Jewels of the Solar System

The four Galilean satellites of Jupiter in Figure 15.1 (Io, Europa, Ganymede, and Callisto) were discovered by Galileo Galilei in 1610. He recognized that the four celestial bodies revolve around Jupiter much like the planets of the solar system revolve around the Sun in the heliocentric cosmology of Copernicus. However, for several centuries the Galilean satellites remained mere points of light that accompanied Jupiter in its orbit around the Sun. More recently, optical spectra of sunlight reflected by the Galilean satellites indicated the presence of water ice on their surfaces (Pilcher et al., 1972). The modern era of exploration of the Galilean satellites started in 1979 when Voyagers 1 and 2 recorded spectacular images of all four satellites. Still more information was obtained by the spacecraft Galileo while it orbited Jupiter from December 7, 1995 to September 19, 2003. Summaries of the physical and orbital properties of the Galilean satellites have been published in books by Hunt and Moore (1981), Morrison (1982), Beatty and Chaikin (1990), Beatty et al. (1999), Weissman et al. (1999), McEwen et al. (2000), Harland (2000), Fischer (2001), Hartmann (2005), and Greenberg (2005).

15.1 Physical Properties and Celestial Mechanics

The physical and chemical properties of the Galilean satellites support the hypothesis that they formed in orbit around Jupiter soon after the planet itself had come into existence by accretion of its core and while it was attracting hydrogen, helium, and other volatile compounds that had formed a disk in orbit around it. The subsequent evolution of the Galilean satellites continues to be affected by finely tuned orbital resonances and by the strong body-tides raised by Jupiter.

15.1.1 Physical Properties

The Galilean satellites are spherical objects whose diameters and masses in Table 15.1 exceed those of all other satellites of Jupiter listed in Table 14.2. In addition, their bulk densities in Figure 15.2 decrease with increasing distance from the center of Jupiter starting at 3.530 g/cm^3 for Io to 1.790 g/cm^3 for Callisto compared to 3.34 g/cm^3 for the Moon. The albedos of the Galilean satellites are exceptionally high ranging from 63% for Io to 17% for Callisto compared to only 11% for the Moon. As a result of their comparatively small masses, the escape velocities of the Galilean satellites are between 2.740 km/s for Ganymede and 2.040 km/s for Europa, all of which are similar to the escape velocity of the Moon (2.380 km/s). Although Io has a very tenuous atmosphere of sulfur dioxide (SO_2) released by virtually continuous volcanic eruptions, the surfaces of the other Galilean satellites, like the surface of the Moon, are exposed to the vacuum of interplanetary space.

The high albedo of Io (63%) is caused by the presence of light-colored sulfur and its compounds that cover the underlying basalt lava which continues to be erupted by the numerous active volcanoes that dot its surface. The high albedos of the other Galilean satellites compared to that of the Moon arise because their icy surfaces reflect sunlight much more efficiently than the basalt surface of the Moon. Nevertheless, we note that the albedos of Europa (64%), Ganymede (43%), and Callisto (17%) decrease with increasing distance from Jupiter. The apparent darkening of the ice surfaces of the

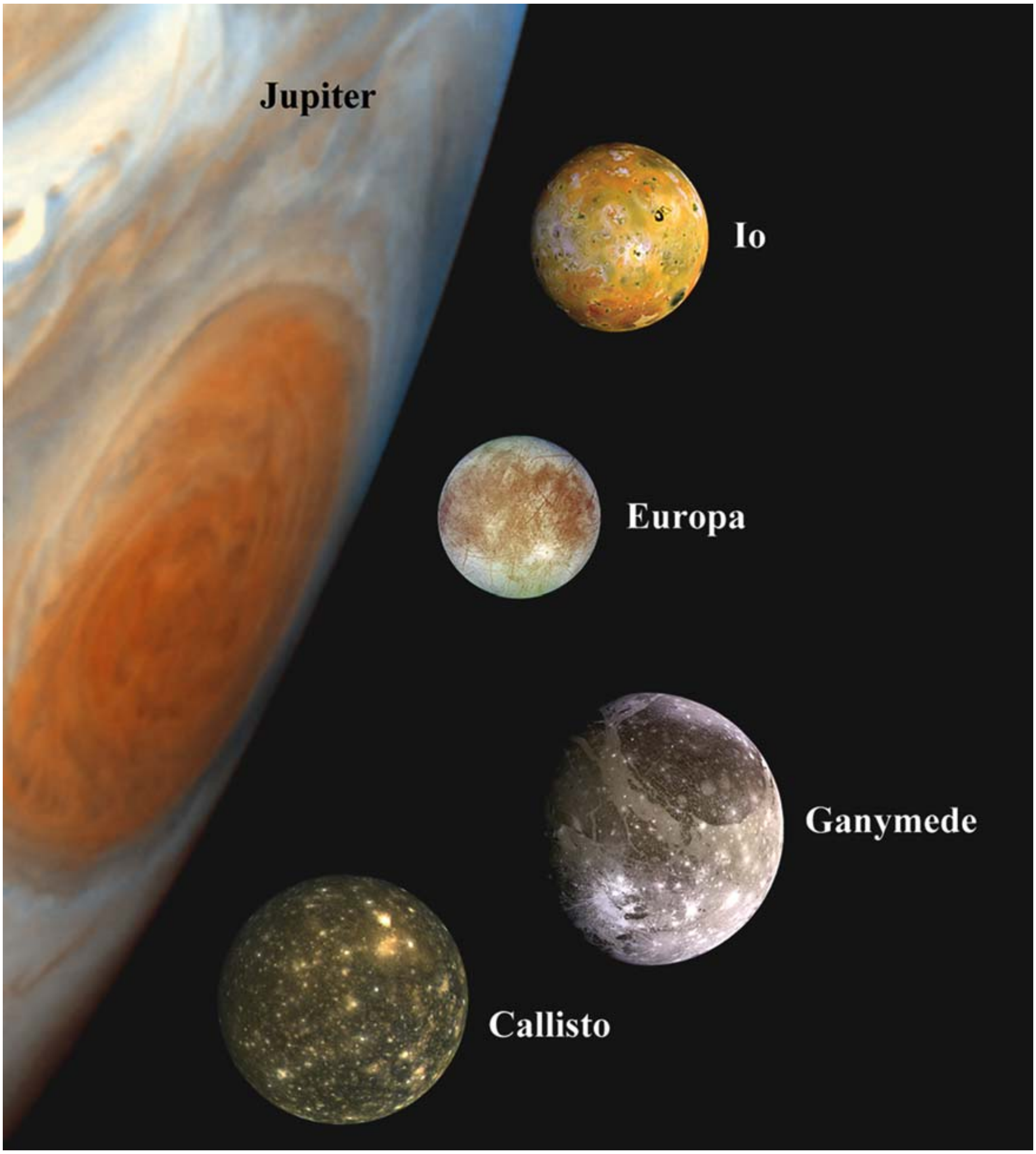

Figure 15.1. The montage of the Galilean satellites of Jupiter was assembled from images recorded by the spacecraft Galileo in 1996 (Io, Europa, and Ganymede) and by the Voyagers in 1979 (Callisto). Each of these satellites is a substantial world characterized by unique physical and chemical properties. Io has the largest number of active volcanoes, Europa has an ice crust underlain by an ocean of salty water, Ganymede is the largest and most massive satellite in the solar system, the interior of Callisto is undifferentiated and its crust is densely cratered. With the exception of Europa, all of the Galilean satellites are larger and more massive than the Moon of the Earth. (Courtesy of NASA)

Galilean satellites also occurs on the surfaces of other ice-covered satellites in the outer part of the solar system. The principal reasons for this phenomenon include:

1. The ice surfaces are covered with regolith resulting from meteorite impacts, by deposition of Interplanetary Dust Particles (IDPs), and by the accumulation of refractory

Table 15.1. Physical and orbital properties of the Galilean satellites and of the Moon (Hartmann, 2005)

Property	Io	Europa	Ganymede	Callisto	Moon
Physical Properties					
Diameter, km	3630	3130	5280	4840	3476
Mass, kg	8.89×10^{22}	4.79×10^{22}	1.48×10^{23}	1.08×10^{23}	7.35×10^{22}
Density, g/cm^3	3.530	3.030	1.930	1.790	3.34
Albedo, %	63	64	43	17	11
Escape velocity, km/s	2.560	2.040	2.740	2.420	2.380
Atmosphere	thin SO_2	none	none	none	none
Orbital Properties					
Semi-major axis, 10^3 km	422	671	1071	1884	384.4
Period of revolution, d	1.769	3.551	7.155	16.689	27.32
Period of rotation, d	1.769	3.551	7.155	16.689	27.32
Orbital eccentricity	0.000	0.000	0.002	0.008	0.055
Inclination of orbit to equat. plane of Jupiter	0.03°	0.46°	0.18°	0.25°	—

dust particles that originally formed in the solar nebula and are being released as the ice sublimates into the vacuum of interplanetary space.

2. The ice contains organic compounds (e.g., CH_4 and other hydrocarbons) that may disintegrate by exposure to ultraviolet radiation and energetic nuclear particles of the solar wind and of cosmic rays leaving a black residue of amorphous carbon and carbonaceous matter of high molecular weight.

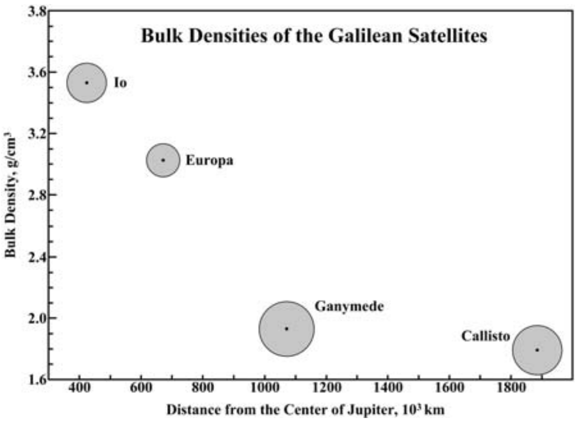

Figure 15.2. The bulk densities of the Galilean satellites decrease with increasing distance from the center of Jupiter. This relationship implies that the amount of water ice relative to rocky material increases similarly, which supports the hypothesis that these satellites formed in orbit around Jupiter from a disk of gas and dust. The diameters of the satellites are approximately to scale

Both processes described above can cause the ice surfaces of the Galilean satellites to darken with increasing exposure age as recorded by the number of meteorite-impact craters per unit area. This conjecture is supported by the observation that the crater density of Callisto (albedo = 17%) approaches saturation, whereas the surface of Europa (albedo = 64%) contains only a few craters and the surface of Ganymede (albedo = 43%) includes areas of dark and heavily cratered ice surrounded by light-colored and sparsely cratered terrain. We conclude from these comparisons that the surface of Europa is rejuvenated by an on-going process, which implies that it is still geologically active, whereas Callisto has not been rejuvenating its surface because it is geologically inactive. Once again, Ganymede is the satellite "in the middle" because it is less active than Europa but more active than Callisto. In spite of the differences in the exposure ages of the surfaces, all of the Galilean satellites formed 4.6 billion years ago at the same time as all of the planets of the solar system.

The bulk densities of the Galilean satellites in Figure 15.2 decrease smoothly with increasing distance from the center of Jupiter. In this regard, the Galilean satellites resemble the terrestrial planets whose bulk densities in Figure 3.6 also decrease with increasing distance from the Sun. The elevated but variable bulk densities imply that the Galilean satellites have different internal structures including iron-cores (Io, Europa, and Ganymede), and mantles composed of silicate minerals (Europa and Ganymede) as shown in Figure 15.3. In spite of these generalizations, the physical properties of each of the Galilean satellites distinguish it from its neighbors. For example, the mantle of Io appears to be molten, the upper mantle of Ganymede consists of a mixture of ice and rocky material, and the interior of Callisto is composed of an ice-rock mixture that has only partially differentiated (i.e, Callisto does not have an iron-rich core). In addition, the outer crust of Io consists of silicate rocks, whereas the crusts of Europa, Ganymede, and Calisto are composed of water ice and the ice crust of Europa is known to float on a global ocean of liquid water. Liquid water may also be present under the ice crusts of Ganymede and Callisto (Johnson, 1999).

The apparent internal homogeneity of Callisto is especially interesting because it indicates that this body has not been heated sufficiently to cause the refractory constituents to sink to the center and for the ice to segregate as it did in the interiors of Ganymede and Europa. Therefore, Callisto may have preserved the initial state of the other Galilean satellites after their formation by accretion of particles composed of ice and refractory materials. In contrast to Callisto, all of the other Galilean satellites evolved by internal differentiation in response to heat provided primarily by on-going tidal heating caused by Jupiter and by the decay of radioactive isotopes of U, Th, and K.

Io is a special case because it no longer contains water or other volatile compounds, except those of sulfur, because of strong heating by tidal friction. The resulting heat-flow to the surface of Io has been estimated at more than 2.5 Watts/m^2, which is about five times greater than the average global heat-flow of the Earth (0.06 Watts/m^2) and even exceeds the heat-flow at the active geothermal area at Wairakei in New Zealand (1.7 Watts/m^2). Evidently, the tidal heating of Io is quite sufficient to account for the eruptions of basalt lava by the numerous active volcanoes on its surface. For the same reason, the continuing geological activity of Europa and Ganymede is attributable to tidal heating, in the absence of which these bodies would have long ago become inactive like the Moon.

The cores of Io, Europa, and Ganymede are described as being "iron-rich" in composition because the available data do not distinguish between metallic Fe-Ni alloys and sulfides of Fe, Ni, and other chalcophile metals. The composition of the core determines its density and hence its predicted radius. For example, if the core of Io is composed of iron sulfide, its radius is 52% of the planetary radius. If the core consists of metallic iron, its radius is only 36% of the planetary radius (1820 km) (Hartmann, 2005). In addition, questions remain whether the cores are liquid or solid. For example, Johnson (1999) suggested that the iron core of Ganymede may be partly molten. If the cores of Io, Europa, and Ganymede are at least partly liquid, they may permit electrical currents to induce magnetic fields. This matter will be addressed elsewhere in this chapter with respect to each of the Galilean satellites.

15.1.2 Celestial Mechanics

The lengths of the semi-major axes of the orbits of the Galilean satellites in Table 15.1 range from 422×10^3 km (Io) to 1884×10^3 km (Calisto), which means that Callisto is about 4.5 times farther on average from the center of Jupiter than Io. The radii (r) of the orbits of Io and Europa and of Ganymede and Europa are related by a factor of about 1.59 as shown below:

$$\frac{\mathrm{r(Europa)}}{\mathrm{r(Io)}} = \frac{671 \times 10^3}{422 \times 10^3} = 1.590$$

$$\frac{\mathrm{r(Ganymede)}}{\mathrm{r(Europa)}} = \frac{1071 \times 10^3}{671 \times 10^3} = 1.596$$

The value of the orbital radius-ratio for Callisto relative to Ganymede rises to 1.759. Nevertheless, these apparent regularities among the orbital radii of the Galilean satellites are the basis for similar regularities of their periods of revolution as required by Kepler's third law.

The data in Table 15.1 indicate that the periods of revolution (p) of the Galilean satellites are

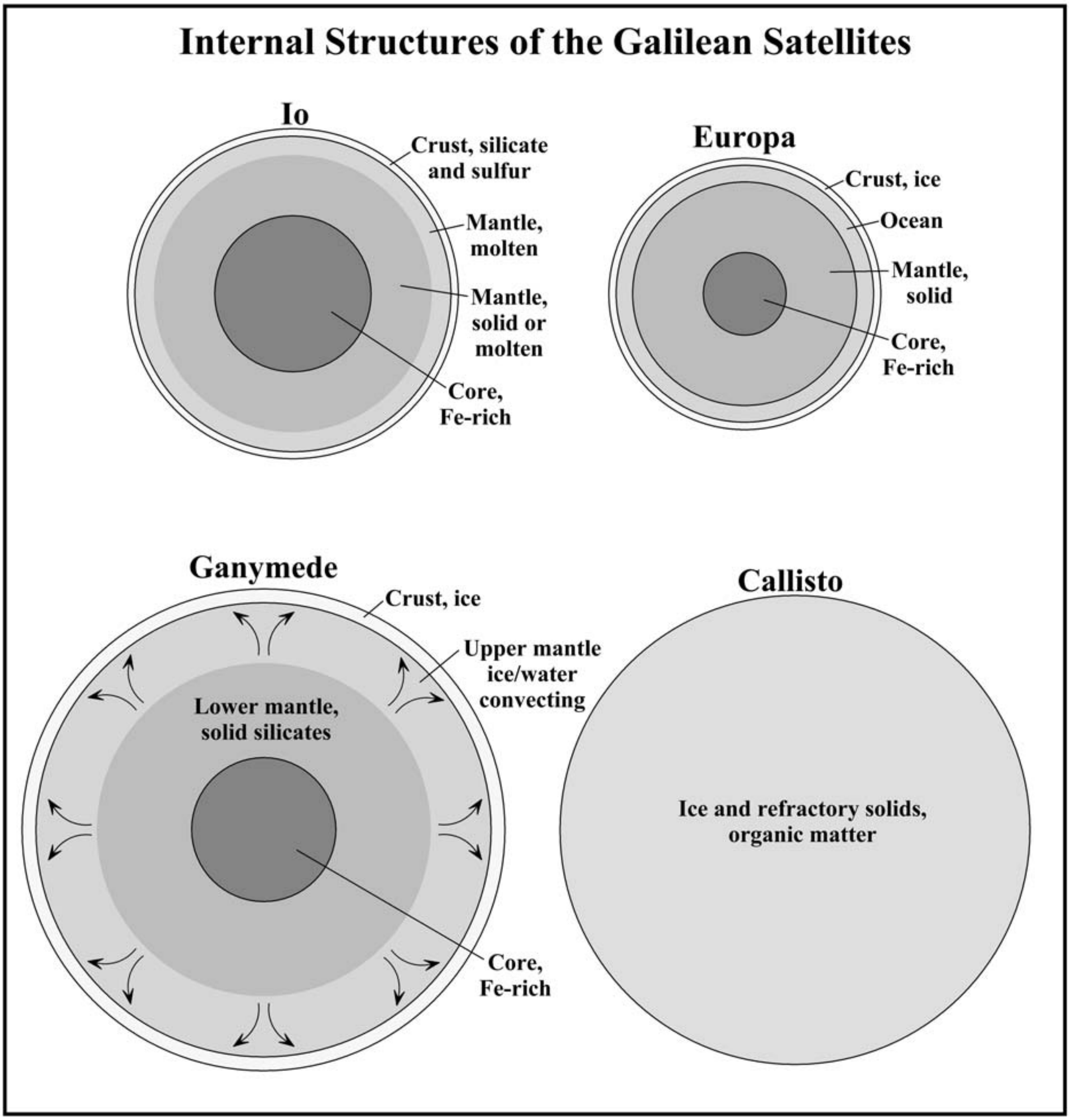

Figure 15.3. Internal structures of the Galilean satellites drawn to scale. Io, Europa, and Ganymede have differentiated into an Fe-rich core, a silicate mantle, and a crust composed of basalt and sulfur (Io) or ice (Europa and Ganymede), whereas Callisto is composed of an undifferentiated mixture of ice and solid particles of refractory compounds and metallic iron. The ice may also contain organic matter similar to that of carbonaceous chondrites. The accumulation of refractory dust particles and of organic matter imbedded in the ice and the deposition of interplanetary dust particles and meteoritic debris cause the surfaces of Europa, Ganymede, and Callisto to darken with increasing exposure age. Adapted from Hartmann (2005, Figure 8.28) with input from Johnson (1999) and Freedman and Kaufmann (2002)

surprisingly short and range from 1.769 days (Io) to 16.689 days (Callisto) compared to 27.32 days for our Moon (Science Brief 15.6.1). The ratios of the periods of neighboring satellites are very nearly whole numbers:

$$\frac{\text{p(Europa)}}{\text{p(Io)}} = \frac{3.551}{1.769} = 2.007$$

$$\frac{\text{p(Ganymede)}}{\text{p(Europa)}} = \frac{7.155}{3.441} = 2.014$$

$$\frac{\text{p(Callisto)}}{\text{p(Ganymede)}} = \frac{16.689}{7.155} = 2.332$$

These results tell us that the period of Europa is twice as long as the period of Io. Therefore, when Io and Europa start their revolutions when they are aligned along a straight line that passes through the center of Jupiter (i.e., when they are in conjunction), the two satellites come back into conjunction after two revolutions for Io and one for Europa:

Io: $1.769 \times 2.007 = 3.550$ days
Europa: $3.551 \times 1.000 = 3.551$ days

In other words, Io and Europa move into conjunction every 3.551 days at very nearly the same location in their orbits and therefore interact gravitationally on the same schedule. This kind of gravitational interaction is referred to as *resonance* and is specified by the fraction 1/2, where the numerator and denominator indicate the number of revolutions completed by two objects in the same length of time. (See also the Kirkwood gaps of asteroids in Section 13.3).

The periods of revolution of Europa and Ganymede are also in resonance because Europa completes 2.014 revolutions in the same time Ganymede completes one. The periodic gravitational interactions of the Galilean satellites at successive conjunctions affect the eccentricities of their orbits in ways that were elucidated by the calculations of the French mathematician *Pierre-Simon Laplace* in the early part of the 19th century. It turns out that the conjunctions of Io and Europa occur when Europa is at the aphelion of its orbit known also as the *apojove*. The conjunctions of Europa with Ganymede occur at the opposite end of Europa's orbit at a point called the *perijove* (i.e., perihelion). Consequently, when Europa and Ganymede are in conjunction on one side of Jupiter, Io is on the other side.

The eccentricities of the orbits of the Galilean satellites that result from the resonance of their periods of revolution cause their distances from the center of Jupiter to vary during each orbit. These variations in turn determine the amount of deformation of the satellites by the tidal forces exerted by Jupiter. The constant changes in the shapes of the Galilean satellites generates heat by internal friction, which explains why Io, Europa, and Ganymede continue to be geologically active. The differential tidal force decreases as the reciprocal of the cube of the distance (Hartmann, 2005, p. 52). Therefore, the amount of tidal heat generated in the Galilean satellites decreases steeply with increasing distance from Jupiter such that Callisto is virtually unaffected by tidal heating and has remained geologically inactive throughout the history of the solar system.

At this point we pause to consider that the eccentricities of the orbits of Io and Europa in Table 15.1 are listed as 0.00 even though we know that the heat produced by tidal friction in these satellites is caused by the eccentricity of their orbits. This discrepancy arises because the orbital eccentricities of the Galilean satellites are the sums of two parts known as the free and the forced components. The *free* component arises from a combination of the distance and velocity of a satellite after it formed in orbit around a planet. In accordance with Kepler's third law, the orbit of a satellite at a specified distance from the center of the planet is circular *only* in case the orbital velocity has exactly the required value. The *forced* component of the eccentricity arises from the gravitational interactions of two satellites whose orbital periods are in resonance. Although the magnitudes of the two components are constant, the direction of the long axis of the orbit corresponding to the forced eccentricity changes with time. Therefore, the free and forced eccentricities are added as though they are vectors. In case the directions are identical, the total eccentricity is the sum of the magnitudes of the free and the forced components. In case the forced component has a different direction than the free component, the total eccentricity is less than the sum of the magnitudes of the two components. The eccentricities of the Galilean satellites in Table 15.1 indicate only the magnitudes of the free component rather than the magnitudes of the actual eccentricities which vary continuously with time because of changes in the direction of the forced component (Greenberg, 2005, Section 4.3).

The data in Table 15.1 also indicate that the periods of rotation of all four Galilean satellites are equal to their respective periods of revolution. In other words, all four Galilean satellites have spin – orbit coupling of 1:1 just like the Moon does as it revolves around the Earth. Consequently the amount of heat generated by tidal friction in a Galilean satellite in Figure 15.4 depends only on the actual eccentricity and on the length of the semi-major axis of its orbit. The rate of rotation does not contribute to the heat production because the satellites do not appear to rotate when viewed from Jupiter.

The periods of revolution of all four Galilean satellites are longer than the period of rotation of Jupiter (9.84 h). Therefore, the gravitational interactions between Jupiter and the Galilean satellites cause their orbital velocities to increase (Section 9.7.2). As a result, the period of rotation of Jupiter is rising (i.e., its rate of rotation is decreasing) and the lengths of the semi-major axes of the Galilean satellites are increasing (i.e., they are moving farther away from Jupiter). These changes in the relation between Jupiter and its Galilean satellites are based on theoretical considerations and have not actually been observed. In addition, we note that the planes of the orbits of the Galilean satellites are closely aligned with the equatorial plane of Jupiter, whereas the orbits of the two sets of the outer satellites are steeply inclined to the equatorial plane.

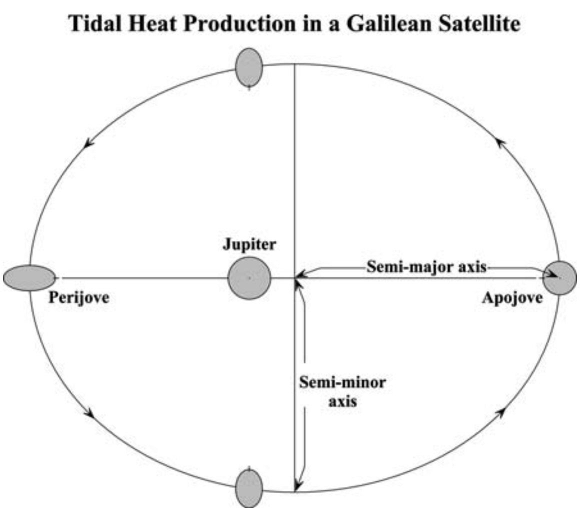

Figure 15.4. Heat generation in a Galilean satellite by tidal friction is caused by the deformation of its spherical shape depending on its distance from Jupiter. The maximum deformation occurs at perijove (perihelion) when the satellite is closest to Jupiter. The least deformation occurs at apojove (aphelion) when it is farthest from Jupiter. The extent of the deformation at perijove is greatest for Io and smallest for Callisto because the size of the tidal bulge decreases by a factory of $1/r^3$ with increasing distance (r) from the center of Jupiter. Consequently, Io is heated sufficiently to be the most volcanically active body in the solar system, whereas Callisto is virtually unaffected by tidal heating and has remained close to its initial state following its accretion. The tick marks on the satellite demonstrate 1:1 spin-orbit coupling

15.1.3 Origin: Alternative Hypotheses

The physical and chemical properties of the Galilean satellites and the celestial mechanics of their orbits, to the extent they are known to us, can be used to state alternative hypotheses concerning the origin and subsequent evolution of these satellites of Jupiter. The most plausible hypotheses rely on analogies with the origin of the Sun and the solar system.

The decrease of the densities of the Galilean satellites with increasing radii of their orbits implies that the abundance of water ice increases with distance from Jupiter and that the abundance of silicates of Fe, Ca, and Mg decreases. This kind of differentiation is *inconsistent* with the hypothesis that the Galilean satellites were captured by Jupiter in a sequence of random events. Instead, the systematic differences in the bulk chemical compositions of the Galilean satellites remind us of the differences in the chemical compositions of the terrestrial planets of the solar system which also vary systematically as a function of distance from the Sun (Section 3.5). Therefore, the Galilean satellites may have formed within a disk of gas and dust that was revolving around Jupiter. The dust particles consisted of water ice and refractory materials such as silicates and oxides as well as small grains of metallic iron or iron sulfide. The gas was composed of hydrogen and helium in approximately solar proportions. The Galilean satellites formed only by the accumulation of the solid particles because their gravitational fields were not strong enough to attract and hold atmospheres composed of hydrogen and helium.

The present internal homogeneity of Callisto indicates that the accumulation of dust particles did not release enough energy to cause the satellites to melt. Instead, Io, Europa, and Ganymede were heated by tidal friction depending on their respective average distances from Jupiter. According to this hypothesis, Io lost virtually all of the water ice by melting and direct sublimation as a result of tidal heating, whereas Europa developed an ice crust that covers an ocean of liquid water. Ganymede also has an ice crust that rests on an undifferentiated mixture of ice and rocky material that is convecting in response to temperature-dependent differences in density.

Alternatively, ice crystals that existed in the revolving disk of gas and dust close to Jupiter may have been sublimated by heat radiated from the planet. This heat could have originated by the compression of gases in the atmosphere of Jupiter and from other sources (e.g., decay of radionuclides). In this case, Io may not have contained water or other volatile compounds at the time of its formation, except compounds of sulfur (e.g., FeS). The water vapor released by sublimation of ice particles in the vicinity of Jupiter may have condensed into ice in the colder regions of the disk outside of the orbit of Io and thereby increased the amount of water ice in Europa, Ganymede, and Callisto.

15.2 Io, the Hyperactive Princess

When Voyager 1 approached Io during its flyby in March of 1979, eight plumes were seen on its surface (Smith et al., 1979). When Voyager 2 passed by Io five months later in July 1979, most of these plumes were still active. When the spacecraft Galileo flew by Io again in 1996, about half of the volcanoes that were active in 1979 were still erupting and several others that had been dormant before were then active. The volcanic activity of Io in Figure 15.5 was a surprise because the mass and volume of Io in Table 15.1 are similar to those of our Moon. But instead of being geologically inactive like the Moon, Io has a larger number of active volcanoes than any other planet or satellite in the solar system. The volcanic activity on Io was actually predicted by Peale et al. (1979) in a paper that was published only one week before the images beamed back to Earth by Voyager 1 confirmed the existence of volcanoes on Io. The authors of this paper based their prediction on the amount of tidal heat generated by the *forced eccentricity* of Io's orbit (0.004) caused by the resonance with Europa. In spite of having noon-time surface temperatures between −148° and −138 °C and even though it should have lost most of the original heat it acquired at the time of its formation, Io's upper mantle consists of molten silicate because of the heat produced by tidal friction (Johnson, 1999).

15.2.1 Volcanoes

The images of Io returned by the Voyager spacecraft in 1979 and by the spacecraft Galileo (1995–2003) indicate that its surface contains more than 100 *volcanoes* or "hotspots" where lava flows are being erupted intermittently. A few of the most prominent volcanoes are identified in Table 15.2. The volcanoes are dispersed over the entire surface of Io rather than occurring only in certain kinds of tectonic settings as on the Earth (Faure, 2001). Io also lacks impact craters on its surface because the constant volcanic eruptions are covering them up as soon as they form.

The names of the volcanoes of Io are derived from deities of Volcanoes and Fire in the mythology of different cultures. For example, the large volcano *Pele* was named after the Hawaiian goddess of Fire, *Loki* was a one of the gods in Norse mythology who assisted the more powerful gods Thor and Odin with his clever but devious plans, and *Prometheus* of Greek mythology stole fire from the gods and gave it to humans (Houtzager, 2003).

The colorful surface of Io initially suggested that the volcanoes are erupting liquid sulfur. However, measurements by the spacecraft Galileo indicated that the lava flows are very hot with temperatures that range up to about 1750 °C, which means that they are composed of molten silicates rather than of molten sulfur. The high temperature implies that the recently extruded lava flows on Io are composed of Mg-rich basalt similar to komatiite that was erupted during the Early Archean Era (3.8 to 3.5 Ga) on the Earth (Faure, 2001, p. 385). Rocks of this composition were first described in 1969 from the greenstone belts of the Barberton

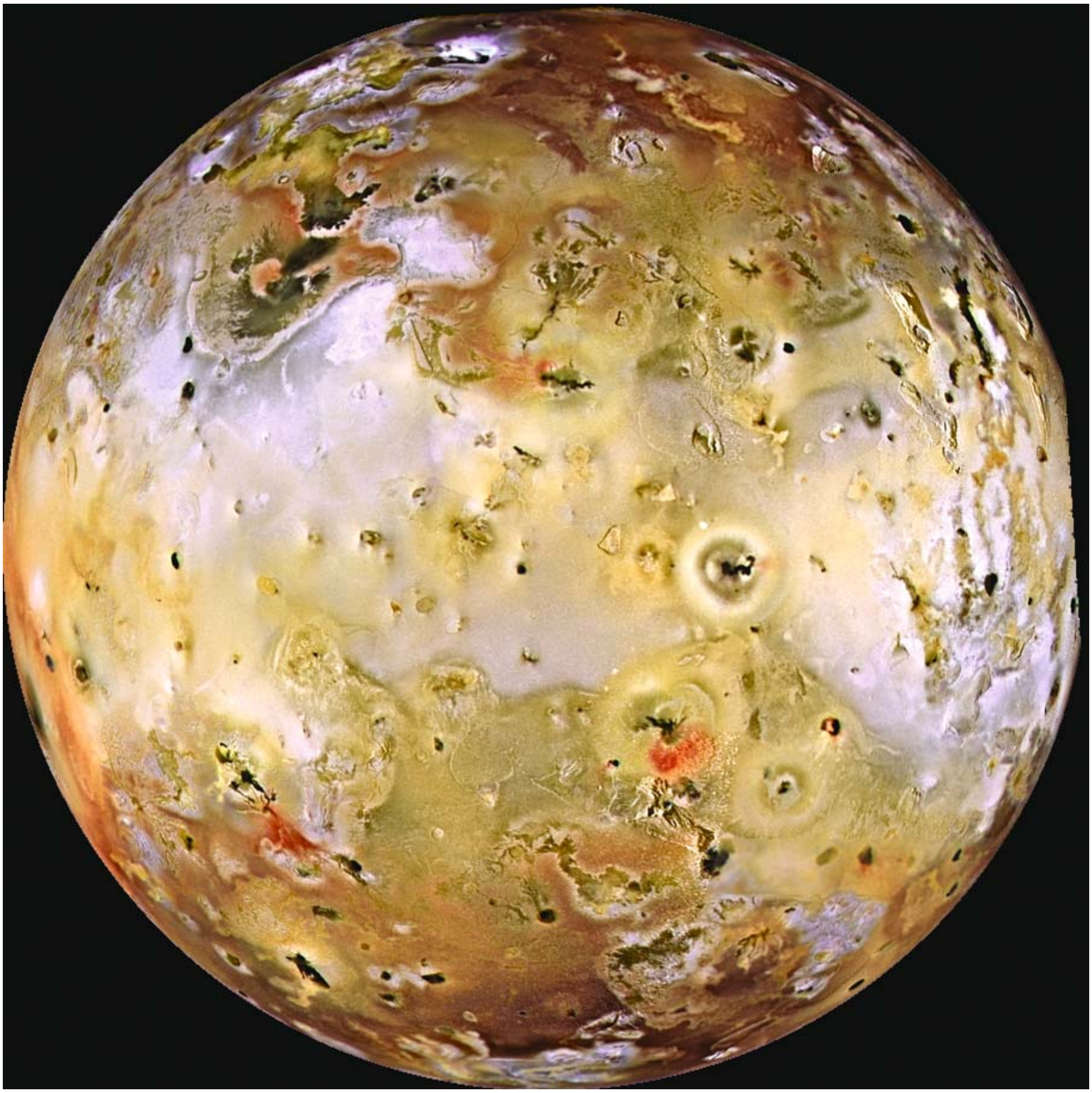

Figure 15.5. The surface of Io is pockmarked by volcanoes many of which are presently active although some may be dormant. The volcanoes of Io are scattered randomly over its surface, which indicates that the volcanic activity is not a symptom of internal tectonic processes as it is on the Earth. The surface of Io also contains rugged mountains several kilometers in elevation, plateaus composed of layered rocks, and large calderas. However, impact craters are virtually absent because they are buried by lava flows and volcanic ash soon after they form. The surface of Io is colored by deposits of native sulfur that is erupted by the volcanoes together with lava flows of molten silicate at high temperature. Io has 1:1 spin-orbit coupling with Jupiter. The view in this picture is of the side of Io that faces away from Jupiter. (PIA 00583, project Galileo, courtesy of NASA/JPL-Caltech /University of Arizona/LPL)

Mountains in South Africa and are now known to occur in volcano-sedimentary complexes of Archean age on most continents. The high temperature of lava flows erupted on Io also indicates that the interior of Io is hotter than the interior of the Earth at the present time. In fact, recent interpretations illustrated in Figure 15.3 suggest that the crust of Io (100 km thick) is underlain by a magma ocean (800 km deep) in contrast to the mantle of the Earth which is a plastic solid rather

Table 15.2. Major volcanoes and pateras of Io mentioned in the text (Johnson, 1999)

Name of volcano	Location		Height, km	Width, km
	lat.	long.		
Amirani	25 °N	116°	95	220
Prometheus	2 °S	154°	75	270
Pillan patera[1]	12 °S	244°	—	400
Pele	18 °S	256°	400	1, 200
Loki plume	18 °N	303°	200?	400
Loki patera[1]	13 °N	309°	—	—
Surt	45 °N	338°	300?	1, 200

[1] A patera is a volcano with a low profile on Mars and Io

than a liquid. The existence of a molten layer in the upper mantle of Io explains why the volcanoes on its surface are dispersed randomly over its surface instead of occurring above mantle plumes and long subduction zones as on the Earth (Faure, 2001).

The rate of production of lava, volcanic ash, and sulfur compounds on Io is sufficient to cover its entire surface with a layer about one meter thick in 100 years. Therefore, the absence of impact craters does not mean that Io is somehow shielded from solid objects that still populate interplanetary space. Instead, the impact craters that do form on the surface of Io are buried by the material erupted by the active volcanoes and the associated plumes.

Several prominent hotspots on the surface of Io in Figure 15.5 are surrounded by reddish haloes composed of native sulfur in the form of short chains consisting of three and four atoms (i.e., S_3 and S_4) (Spencer et al., 2000). These compounds polymerize to form the stable yellow form of sulfur which consists of eight atoms (S_8). The white material consists of sulfur dioxide snow that forms when the hot gas emitted by plumes crystallizes at the low temperatures of space and falls back to the surface of Io. The lava flows erupted within the calderas of active volcanoes are initially very bright but then turn black as they cool and form a solid crust.

15.2.2 Plumes

The hotspots on Io in Figure 15.6 are associated with plumes that form umbrella-shaped fountains up to 500 km high, aided by the low gravity of Io and by the absence of an atmosphere. In order to reach such heights, the gas must be emitted at high speeds ranging from 1100 to 3600 km/h which far exceeds the speed of gas emissions by terrestrial volcanoes like Vesuvius, Krakatoa, and Mount St. Helens where gases have reached speeds of only 360 km/h (Freedman and Kaufmann, 2002, p. 307). The first plume was discovered on March 8, 1979, by Linda Morabito in an image recorded by Voyager 1, when the spacecraft approached Io to within 21,000 km of its surface (Matson and Blaney, 1999).

The plumes emit sulfur dioxide gas and varying amounts of particulates composed of solid sulfur dioxide, native sulfur, and silicate minerals derived from the walls of the vent. Accordingly, the deposits that accumulate around the plume vents are mixtures of native sulfur, sulfur dioxide snow, and volcanic ash. Some plumes may be active in the same location for many years while others are short-lived or may change location. In addition plumes may be invisible throughout their existence or become invisible at some time in their lifetime.

The processes that cause the emission of plumes on Io are illustrated in Figure 15.7 (a to d) based on a model developed by Susan Kieffer in 1982 and described by Matson and Blaney (1999). A deposit of sulfur-dioxide snow and/or native sulfur on the surface on the surface of Io in Figure 15.7 a & b is covered by a lava flow. The increase in temperature causes the sulfur dioxide to be vaporized and the resulting gas is discharged through fractures in the lava flow and along its edge as a plume. The plume produced in this way remains active only until the lava flow cools or until the sulfur deposit is exhausted. This mechanism is capable of producing several plumes that may be active at the same time or may form sequentially at different sites in case additional lava flows are extruded. The explosive emission of gas by this mechanism also causes the formation of "rootless" craters which have been observed on Iceland in places where hot lava has covered deposits of water ice (i.e., glaciers and snowfields).

Long-duration plumes are emitted from large subsurface reservoirs depicted in Figures 15.7 c & d. At first, a deposit of sulfur-dioxide snow and native sulfur on the surface of Io is buried deeply by volcanic pyroclastics and

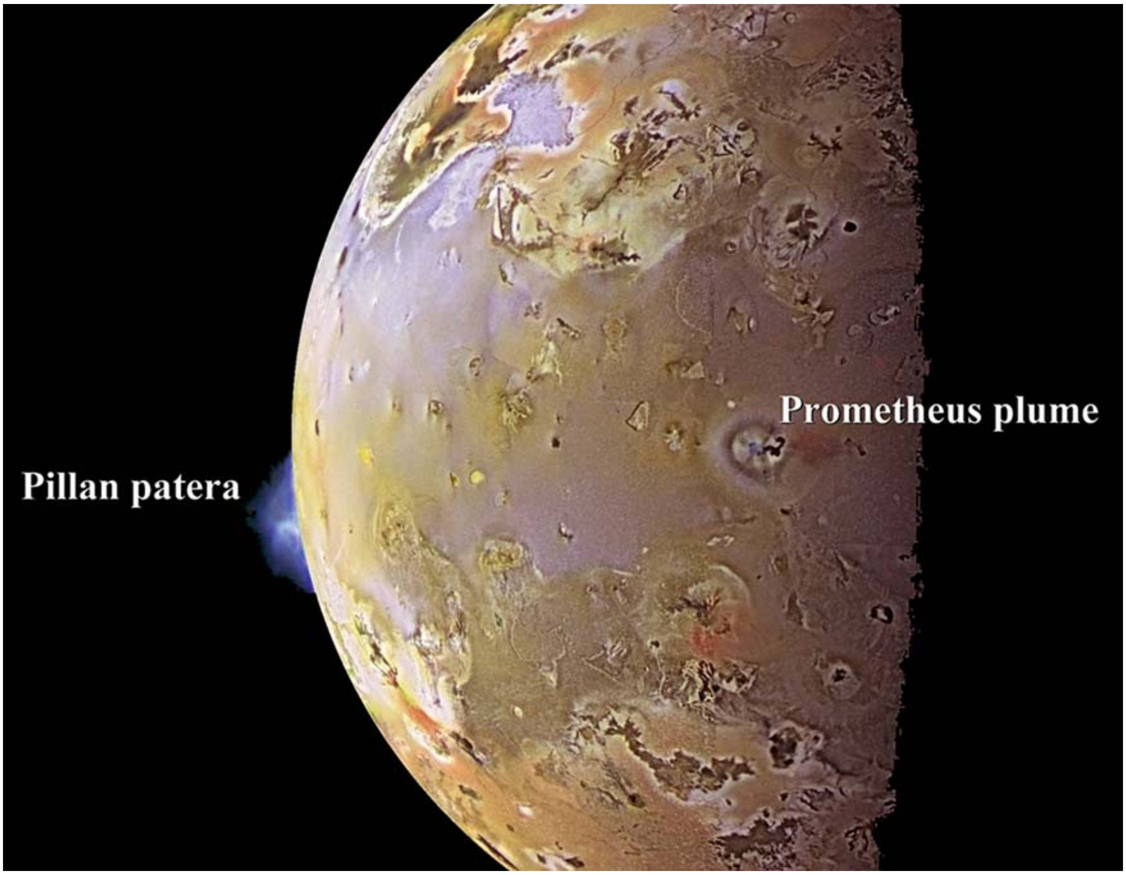

Figure 15.6. The volcanic plume visible along the left edge of Io in this image was erupted by Pillan patera. This plume is 140 km high and consists of sulfur dioxide (SO_2) and fine-grained particulates. A second plume, emitted by the volcano Prometheus, casts a reddish shadow on the surface of Io. The Prometheus plume was first seen in the images recorded by the Voyager spacecraft in 1979 and was still active 18 years later in 1997 when the spacecraft Galileo recorded this image at a distance of more than 600,000 km. (Image PIA 01081, project Galileo, courtesy of NASA/JPL-Caltech/ University of Arizona/LPL)

lava flows. The increase in pressure and temperature converts the solid sulfur-dioxide into a liquid. If the liquid sulfur dioxide is subsequently heated by magma from depth, the resulting gas pressurizes the reservoir which may fracture the roof and allow sulfur-dioxide gas to escape to the surface in the form of a long-lasting and stationary plume. In cases where the material that is emitted consist primarily of sulfur dioxide gas without a significant component of particulates, the resulting plumes are invisible and therefore have been referred to as "stealth" plumes (Matson and Blaney, 1999).

The model developed by Susan Kieffer can explain why some plumes are short-lived whereas others last for years. It can also explain why some plumes appear to migrate and why others are invisible. In addition, the model provides a plausible mechanism for burial of surface deposits of sulfur compounds and the resulting formation of crustal reservoirs of liquid sulfur dioxide and thereby provides a rational basis for the reconstruction of the sulfur-cycle of Io. (Kieffer et al., 2000).

15.2.3 Surface Features

Some of the largest volcanoes on Io (e.g., Prometheus, Loki, Pele, Tvashtar, Pillan, and others) have developed large calderas that contain lakes of cooling lava. In some cases, the lava lakes have formed a solid crust that

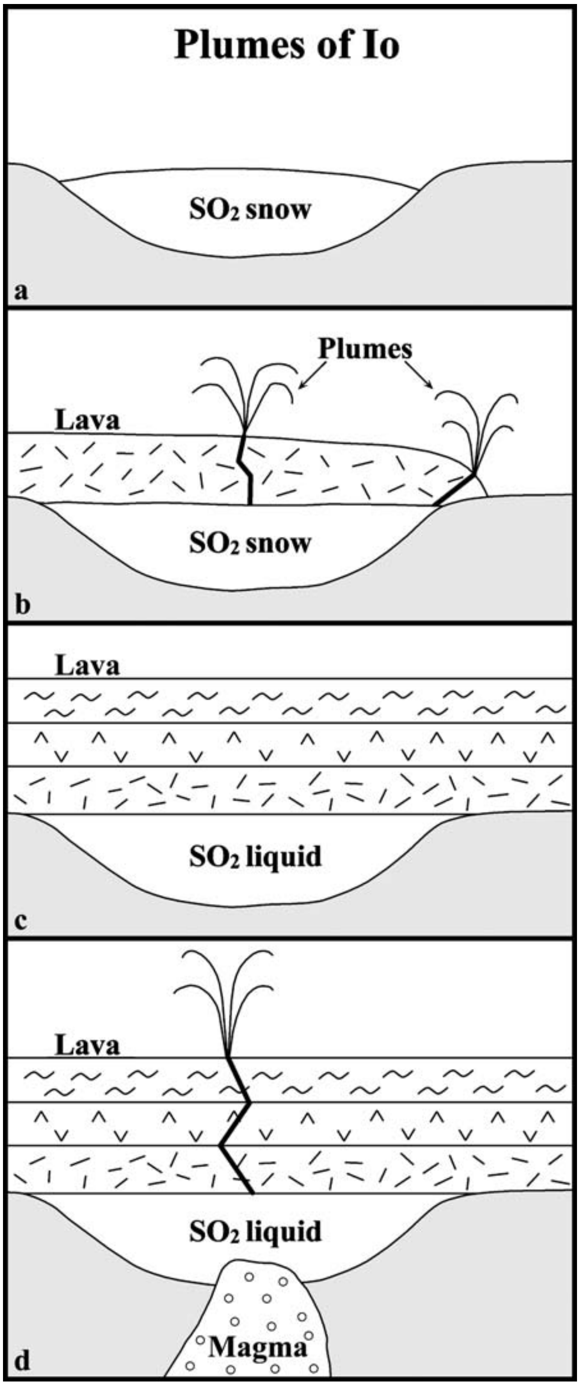

Figure 15.7. a. A depression in the surface of Io was filled by sulfur-dioxide snow (SO_2) that was erupted by a nearby volcanic plume. b. Part of the solid SO_2 snow is vaporized by the heat emanating from lava that covered the deposit. The resulting SO_2 gas escapes through fracture and/or along the edge of the flow to form one or several short-lived plumes. c. A deposit of solid SO_2 snow was buried by several layers of pyroclatics and lava flows. When their total thickness reached one to two kilometers,the pressure they exerted caused the solid SO_2 to liquefy. d. The resulting subsurface reservoir was intruded by silicate magma from depth and the increase in temperature caused the liquid to boil. The resulting SO_2 gas escapes through fractures in the overlying rocks to form a plume composed of gas and dust. Such plumes may be long-lasting but become invisible (i.e., they are stealth plumes) in cases where the gas that is discharged lacks particulates. Adapted from Figure 12 of Matson and Blaney (1999). Not drawn to scale

insulates the hot lava beneath except along the edges where white-hot lava may be exposed (e.g., Tupan). The lava flows and deposits of sulfur compounds emitted by the volcano Culann patera are displayed in Figure 15.8.

The volcanoes Prometheus, Loki, and Pele are located near the equator of Io and are each associated with prominent plumes. The plume of *Pele* reaches a height of 400 km and has caused the deposition of a red ring of elemental sulfur (S_3 and S_4) with a radius of 700 km from the vent. In addition, the lava lake in the caldera of Pele exposes fresh lava along its shore for a distance of about 10 km. A similar phenomenon has been observed on a much smaller scale in the lava lake of Kilauea on the island of Hawaii.

Loki is the most powerful volcano in the solar system because it releases more heat than all of the volcanoes on Earth combined. The caldera of Loki is filled with lava that may have been erupted shortly before the flyby of Galileo on October 10 of 1999. On this occasion, the spacecraft also observed the plume of *Prometheus* which was first seen in the images returned by Voyager 1 in 1979. To everyone's surprise, the plume (75 km high) was now located about 100 km west of its location in 1979. The migration of the plume of Prometheus is explained by the eruption of a new lava flow onto a deposit of sulfur dioxide snow (Figure 15.7b).

The volcano *Tvashtar*, near the north pole of Io, consists of a series of nested calderas within which fountains of hot lava erupted to heights of 1500 m. Lava fountains on Io can reach such heights because of the low gravity and the low viscosity of the lava (e.g., like olive oil), which allows lava to flow for hundreds of kilometers (Lopes, 2002). For example, the lava emanating from the volcano *Amirani* has flowed up to 250 km. The plume of Tvashtar, like that of Pele, reaches a height of 400 km and is depositing

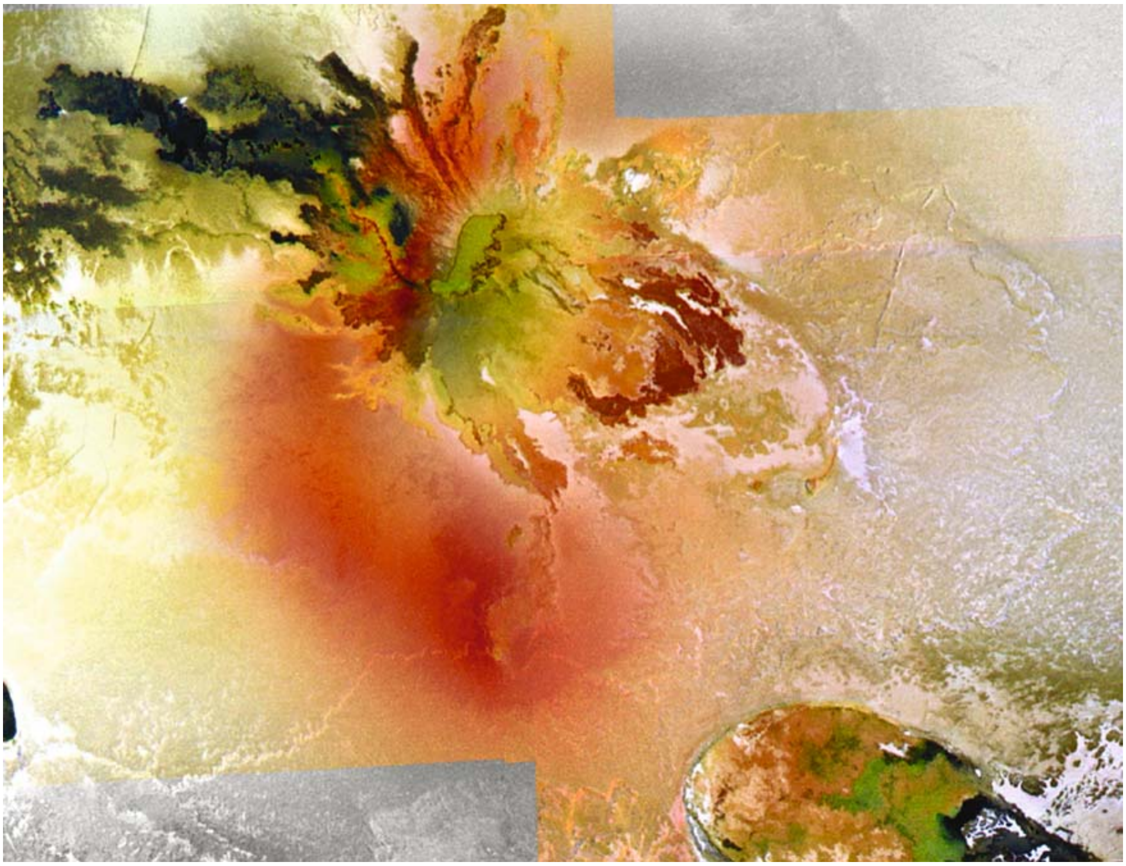

Figure 15.8. Culann patera is one of many active volcanoes on Io. In this image, lava has flowed out of a large caldera in all directions. The diffuse red deposit is native sulfur that was emitted by a plume. This image was recorded in 1999 by the spacecraft Galileo from a distance of 20,000 km. (Image PIA 02535, Galileo project, courtesy of NASA/JPL-Caltech/University of Arizona/LPL)

a reddish ring of sulfur on the area surrounding the vent.

The magnitude and vigor of the Tvashtar plume surprised investigators because all other large plumes occur in the equatorial region of Io. They were even more surprised when the Galileo spacecraft discovered a second large plume about 600 km southwest of Tvashtar during a flyby on August, 6, 2001, when it came within 194 km of the surface of Io. The Tvashtar plume did not even appear in the images taken during this flyby, presumably because it had become a stealth plume, although the Tvashtar volcano was still active. The new plume contained particles composed of sulfur dioxide that rose to a record height of 600 km, thereby exceeding the heights of the plumes of Tvashtar and Pele.

Another unexpected volcanic eruption was observed on February 21,2002, by the Keck II telescope on the summit of Mauna Kea on the island of Hawaii (Marchis et al., 2002). Without warning, a large hotspot developed in two days near the site of the volcano *Surt* located at about 45 °N latitude. The lava erupted at this site had an initial temperature of 1230 °C and covered an area 1,900 square kilometers. The heat released by this eruption came close to equaling the amount of heat released by all other volcanoes on Io.

The image of the caldera of Tvashtar in Figure 15.9, recorded by the spacecraft Galileo on February 22, 2000, includes a flat-topped mesa adjacent to the main lava lake. The near-vertical sides of this mesa are scalloped suggesting that a form of mass wasting is

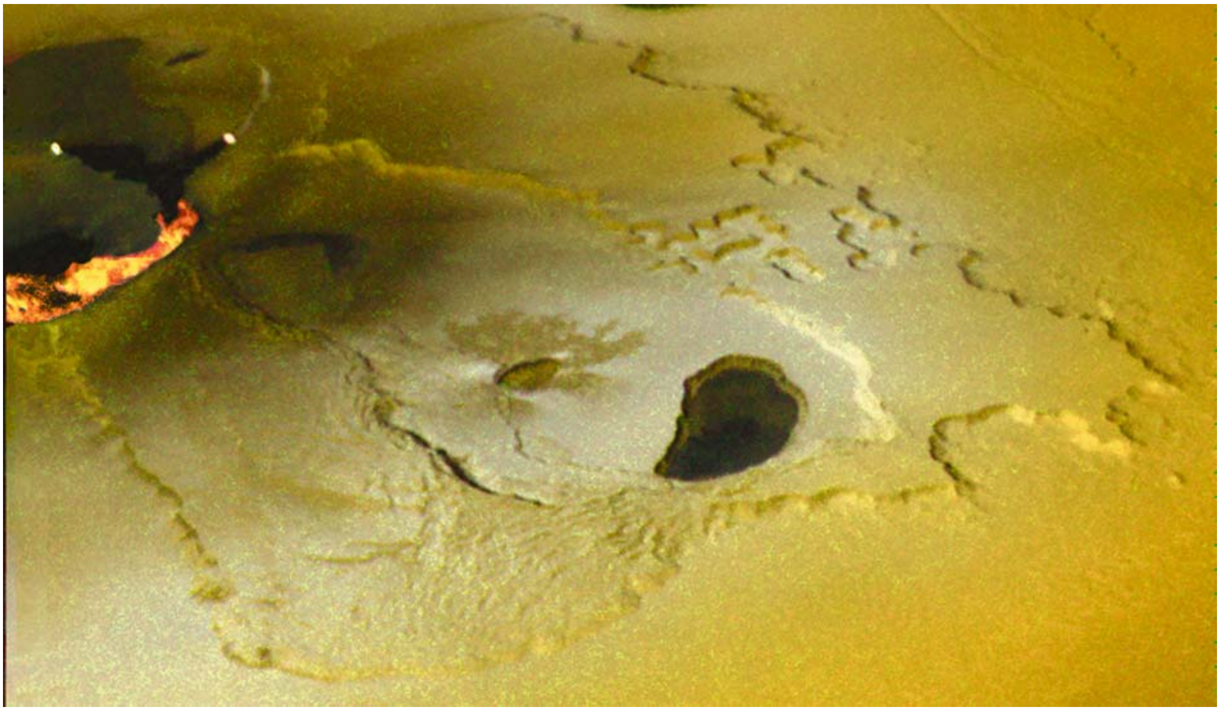

Figure 15.9. Complex of lava lakes in the caldera of the volcano Tvashtar recorded on February 22 of 2000 by the spacecraft Galileo. The caldera, located at 60 °N and 120 °W, was the site of a vigorous eruption in November of 1999 that included lava fountains. The caldera contains several lava lakes which have cooled and appear black in this image. The bright-colored spots are hot lava flows or cracks in the crust of cooling flows. The image indicates that changes are occurring in the topography of this area as a result of the eruption of lava flows and sulfur dioxide. (Image PIA 02550, Galileo project, courtesy of NASA/JPL-Caltech/University of Arizona/HiRise-LPL)

occurring. The erosion of the cliff may be a result of basal sapping caused by a liquid that is discharged by springs at the base of the cliff. The springs may be discharging liquid SO_2 from a subsurface reservoir (Figure 15.7d). The liquid vaporizes instantly in the vacuum at the surface of Io.

The close-up images of the surface of Io also reveal the presence of *mountains* that are not volcanoes but, nevertheless, reach an elevation of 16 km compared to only 8.85 km for Mt. Everest on the Earth. The mountains on Io appear to be the result of uplift of blocks of crust by convection currents in the underlying magma ocean of the upper mantle (McEwen, 1999). The uplifted blocks subside when the pattern of convection in the magma ocean changes and/or because of seismic activity in the crust, which triggers large landslides recorded by ridged debris aprons at the base of the mountains that are visible in images recorded during the Galileo flyby on November 25, 1999.

15.2.4 Interactions with Jupiter

Data collected during flybys of Jupiter by the Pioneer (1973/1974) and Voyager (1979) spacecraft and, most recently, by the Galileo mission (1995 to 2003) indicate that Io interacts significantly with the magnetic field of Jupiter. These interactions cause oscillations in the ambient magnetic field of Jupiter in the vicinity of Io and thereby obscure the evidence concerning the existence of a magnetic field on Io. Therefore, we do not yet know whether Io has a magnetic field (Johnson, 1999; Van Allen and Bagenal, 1999). However, we do know that the orbits of Io and of the other Galilean satellites lie well within the magnetosphere of Jupiter and that Io interacts with Jupiter not only gravitationally but also electromagnetically (Bagenal et al., 2004). For example, the decimetric radiation of Jupiter, mentioned in Section 14.1.1, originates from a toroidal (donut shaped) region that encircles the planet in a plane that dips about 10° to the equatorial plane of Jupiter. The inclination of the torus (donut) matches the tilt of the magnetic moment of Jupiter (9.6°) relative to its axis of rotation. The torus consists of a cloud sodium atoms, positively charged ions of sulfur (S^+) and oxygen (O^+), and electrons (e^-). The sulfur and oxygen ions originate from the decomposition and ionization of sulfur dioxide molecules that are injected into the magnetic field of Jupiter by the plumes of gas and dust discharged by Io. The resulting plasma (ionized gas) is transported all the way around Jupiter by its magnetic field which rotates with the planet at a rate of 9.84 hours per rotation. The electrons are accelerated to high velocities approaching the speed of light (i.e., relativistic velocities) and emit the observed decimetric synchrotron radiation as they move on spiral paths along magnetic field lines in the magnetosphere of Jupiter.

The large number-density of relativistic electrons in the magnetosphere of Jupiter damaged several transistor circuits of the Pioneer 10 and 11 spacecraft as they flew by Jupiter in 1973 and 1974. The dose of radiation they absorbed during their flybys was a thousand times greater than the dose that causes severe radiation sickness or death in humans (Van Allen and Bagenal, 1999, p. 47). The potential for damage of the spacecraft caused by the intense ionizing radiation in the magnetosphere of Jupiter prevented the spacecraft Galileo from attempting close flybys of Io until after the other objectives of the mission had been accomplished.

Measurements by Voyager 1 indicated that the plasma in the torus contains thousands of ions and electrons per cubic centimeter and that the kinetic energies of the ions correspond to a temperature of about 1×10^6 K. In addition, the data reveal that about one tonne of matter per second is being removed from the surface of Io by the magnetic field of Jupiter as it continuously sweeps past the satellite. The bursts of decametric radiation emitted by Jupiter originate from very large electrical currents in the form of current sheets (flux tubes) that connect the plasma of the torus to the ionosphere of Jupiter. The voltage between these terminals is of the order of 400,000 volts and the power generated by the electrical current has been estimated at 2×10^{12} watts.

The energetic plasma derived from Io causes the magnetosphere of Jupiter to expand like a balloon, especially in its equatorial region where the magnetic field of Jupiter is comparatively weak (i.e., 14 times the strength of magnetic field at the equator of the Earth). The magnetosphere is further distorted by the centrifugal force arising from the rapid rotation of Jupiter, which forces the plasma outward into a disk that is aligned with the equatorial plane of the planet. The existence of the so-called *plasma sheet* was directly observed by the Pioneer spacecraft; however, the mechanisms whereby the plasma is heated during its expansion within the magnetosphere of Jupiter is not yet understood but may be related to the rapid rotation of the planet.

The ions and electrons of the plasma that inflate the magnetosphere eventually return to the torus and then cascade into Jupiter's upper atmosphere along lines of magnetic force. The large amount of energy released by this process (10 to 100 trillion watts) energizes the atmosphere in the polar regions of Jupiter and increases its temperature. In addition, this process generates spectacular *auroral displays* of ultraviolet light in the polar regions of Jupiter (Van Allen and Bagenal, 1999, p. 49).

Auroral displays have also been observed in the polar regions of Io when energetic electrons, traveling at high speed along magnetic field lines, collide with molecules in the diffuse atmosphere of Io that is maintained by the eruptions of volcanoes and plumes on its surface. The auroras of Io display a range of colors including bright blue in the equatorial region, red in the polar regions, and green in the night side. The blue glow has been attributed to collisions of energetic electrons with molecules of sulfur dioxide, whereas the red and green auroras are caused by the de-excitation of oxygen and nitrogen atoms, respectively. The auroral displays become weaker when Io passes through the shadow of Jupiter because the resulting decrease of the atmospheric temperature causes the atmospheric gases to condense, thus decreasing the abundance of target atoms and molecules (Geissler et al., 2001).

15.2.5 Summary

Io is the first of the Galilean satellites of Jupiter which dominates it by means of tidal and electromagnetic interactions. Although its orbit appears to be circular, the resonance Io shares with Europa gives rise to a component of forced eccentricity, which enables Jupiter to generate heat within Io by the tidal distortion of its shape. Consequently, Io is the most active body in the solar system with at least 100 volcanoes, several of which are erupting at any given time. The temperature of the lavas erupted by the volcanoes of Io (up to 1750 °C) is higher than the temperature of basalt lava erupted by volcanoes on the Earth. This observation implies that the ionian lavas are similar in composition to Mg-rich komatiites that formed on the Earth during the Early Archean Era by high degrees of partial melting of ultramafic rocks in the mantle of the Earth.

Io formed in orbit around Jupiter by accretion of solid particles in a disk of gas and dust that revolved around the planet at the time of its formation. During this process, ice particles may have evaporated as a result of heat radiated by Jupiter. Alternatively, water that may have been incorporated into Io at the time of its formation later evaporated because of heat generated by tidal friction. In any case, Io has been depleted of water in contrast to the other Galilean satellites which still have thick crusts of ice.

After its formation, Io differentiated into an iron-rich core and a silicate mantle the upper part of which appears to be molten. This reservoir of magma is the source of lava erupted by volcanoes which are randomly distributed over the surface of Io in contrast to the Earth where volcanoes occur in certain well-defined tectonic settings.

The data recorded by the spacecraft Galileo and its predecessors do not indicate unequivocally whether the core of Io is liquid or solid. In any case, the fluctuations of the magnetic field of Jupiter in the vicinity of Io may be caused by electromagnetic phenomena and do not necessarily prove whether or not Io has a magnetic field.

The volcanic activity of Io is accompanied by plumes of sulfur dioxide gas and associated condensation products that rise to great height above the surface. The sulfur dioxide gas condenses in the coldness of space to form snowflakes that are deposited around the vent together with particles of native sulfur and volcanic ash. These deposits account for the coloration of the surface of Io ranging from red to yellow (sulfur) to white (sulfur dioxide snow). Some of the plumes originate when deposits of sulfur dioxide snow are covered by hot lava flows. In cases where deposits of snow are buried deeply (i.e., one to two kilometers), the deposits of solid sulfur dioxide are transformed into subsurface reservoirs of liquid sulfur dioxide. When such a reservoir on Io is heated by the intrusion of hot silicate magma from below, the resulting superheated vapor is expelled in a second kind of plume that resembles a geyser similar to Old Faithful in Yellowstone Park, except that liquid sulfur dioxides takes the place of water.

Io as well as the other Galilean satellites exist within the magnetosphere of Jupiter. Therefore, some of the sulfur dioxide molecules and atoms of other elements are injected into the magnetosphere of Jupiter by the eruption of volcanic plumes on Io. The sulfur dioxide molecules are broken up and the resulting atoms of sulfur and oxygen are converted into positively charged ions by removal of electrons. The resulting energetic plasma is carried away by the magnetic field of Jupiter that continually sweeps past Io as the planet rotates with a period of 9.84 hours. For this reason, Io revolves within a torus (donut) of plasma that surrounds Jupiter. The torus expands to form a plasma sheet close to the equatorial plane of Jupiter. The electromagnetic interactions between Io and Jupiter also cause the emission of the decametric and decimetric radiation and the auroral light displays in the polar regions of Io and Jupiter.

15.3 Europa, the Ice Princess

When the Voyager spacecraft sent back postcards of the Galilean satellites in 1979, Europa appeared to be a cold but serene world whose icy surface in Figure 15.10 gleamed in the reflected light of the Sun. Although first impressions can be misleading, Europa has turned out to be one of the most interesting worlds of the solar system (Greenberg, 2005; Harland, 2000; Kargle et al., 2000; Fischer, 2001; Greeley, 1999).

Europa is the smallest of the Galilean satellites with a radius of 1565 km compared to 1820 km for Io and 2640 km for Ganymede (Hartmann, 2005). Its physical and orbital properties in Table 15.1 indicate that Europa is smaller than

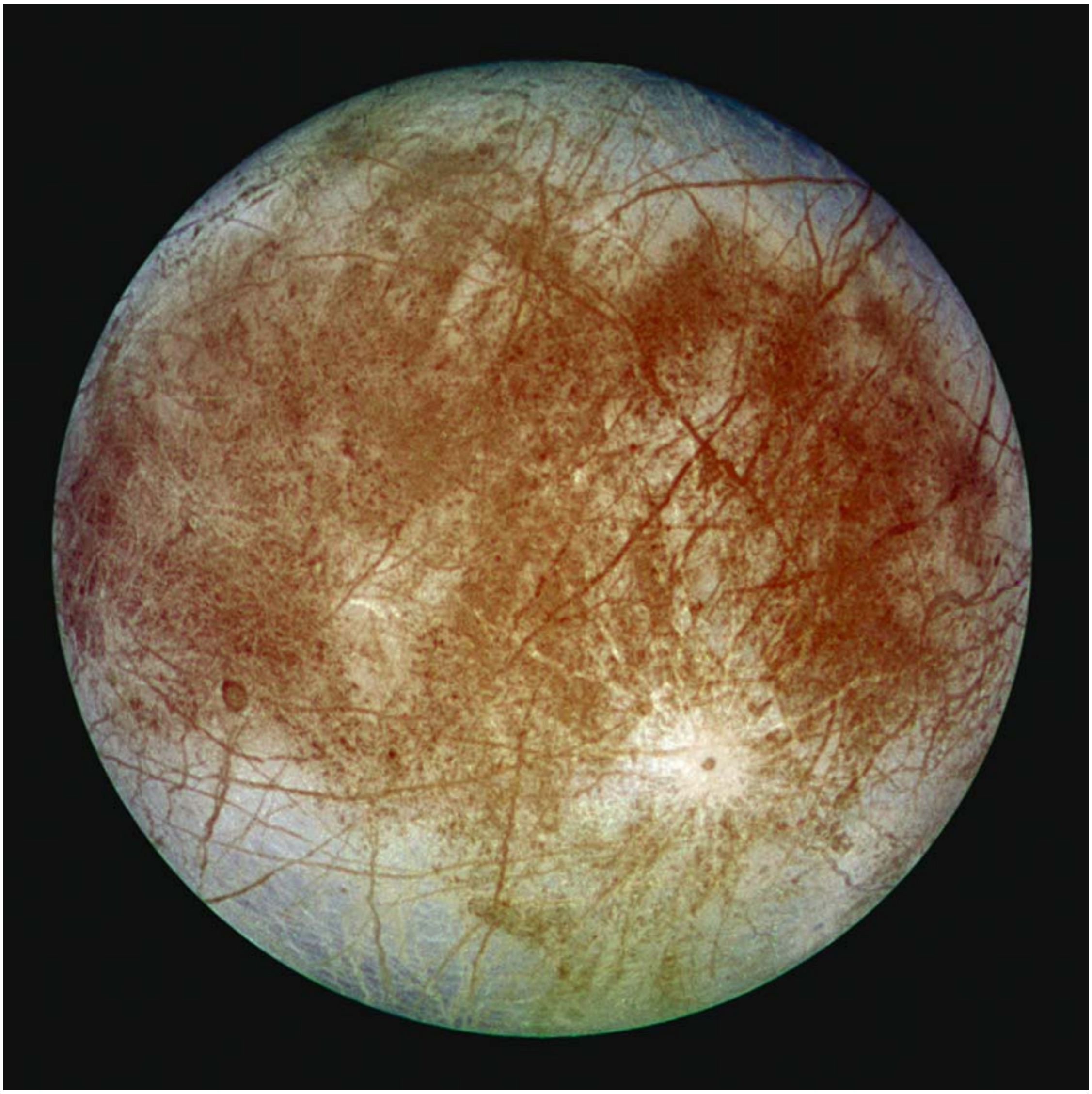

Figure 15.10. Europa is the smallest of the Galilean satellites with a diameter of 3130 km compared to 3476 km for the diameter of the Moon of the Earth. The crust of Europa is composed of water ice and is criss-crossed by innumerable fractures that appear as dark curved lines in this image. The brown discoloration of the surface if caused by deposits of various kinds of salts, meteorite debris, interplanetary dust particles, and organic matter that was embedded in the ice and/or was brought to the surface by water from the ocean beneath the crust. The black spot surrounded by rays of white ejecta is the impact crater Pwyll (diameter = 50 km). Although several other impact craters have been identified, Europa is only sparsely cratered because of the on-going rejuvenation of its surface by the extrusion of water through fractures and melt-throughs. This image shows the trailing hemisphere of Europa which rotates only once during each revolution. (Image PIA 00502, Galileo project, courtesy of NASA/JPL-Caltech. The image was processed by Deutsche Forschungsanstalt für Luft und Raumfahrt, Berlin, Germany)

the Moon and also has a lower mass (4.79×10^{22} kg) and a lower bulk density ($3.030\,g/cm^3$). However, the albedo of Europa (64%) is far higher than that of the Moon (11%) which is consistent with the icy surface of Europa. In fact, only a few other ice-covered satellites have higher albedos than Europa (e.g., the satellites of Saturn: Enceladus 95% and Calypso 80%; as well as Triton 75%, satellite of Neptune). The escape velocity of Europa is 2.04 km/s compared to 2.38 km/s for the Moon, 11.2 km/s for the Earth, and 59.5 km/s for Jupiter. The proximity of Europa to Jupiter will become a problem for spacecraft landing on its surface and taking off again during future exploratory missions. Europa does not have an atmosphere and its calculated average surface temperature is −170 °C, whereas the measured temperatures range from −148 °C at daytime to −188 °C at night (Hartmann, 2005, p. 295).

15.3.1 Ice Crust and Ocean

The crust of Europa is composed of pure water ice and contains only a few impact craters because they are covered almost as rapidly as they form. The on-going resurfacing indicates that Europa is still geologically active and that the tidal heat has allowed the lower part of the ice crust of Europa to remain liquid (Pappalardo et al., 1999). This global ocean acts as a reservoir from which liquid water can be extruded to the surface where it freezes instantly to form "lava flows" of water ice. Evidently, on Europa liquid water takes the place of silicate melts in a process called *cryovolcanism* (Greeley, 1999). Several other ice-covered satellites of Jupiter, Saturn, Uranus, and Neptune are also geologically active because of cryovolcanic activity based on melting and freezing or vaporization and condensation of certain volatile compounds that melt or vaporize at very low temperature (e.g., water, methane, nitrogen, etc.).

The topography of the surface of Europa in Figure 15.11 is dominated by sets of intersecting *double ridge systems* that consist of a narrow central valley (crustal fracture) flanked by continuous and low double ridges. The intersections of the double ridges can be used to reconstruct their sequence of formation because the youngest double ridge cuts across all previously formed ridge systems. The fractures are interpreted to form as a consequence of the tidal deformation of the ice crust. The ridges and valleys virtually saturate the surface to form *ridged terrain*.

The ridges and other kinds of topographic features on the surface of Europa are a few hundred meters in elevation. Therefore, the surface of Europa is not as smooth as it appeared in the images returned by the Voyagers. Instead, the surface is actually quite chaotic and hummocky. There are only a few areas on Europa that are flat and smooth enough to be suitable for the safe landing of a spacecraft. In marked contrast to Io, the surface of Europa does not contain volcanoes and plumes of sulfur dioxide nor are there any fault-block mountains.

In the absence of volcanic eruptions by means of which Io and other geologically active bodies (e.g., the Earth) transport heat from their interiors to the surface, Europa presumably loses heat by convection of water from the bottom of the ocean to the water-ice interface and by conduction through the ice crust. Therefore, the thickness of the crust depends inversely on the amount of heat that needs to be transported to the surface in order to maintain thermal equilibrium. In other words, the more heat needs to be conducted to the surface, the thinner is the crust (Greenberg, 2005). Although the actual thickness of the ice crust of Europa is not yet known, it may vary regionally in case the heat flow from the silicate mantle to the ocean is channeled by hotsprings or by volcanic activity.

The central valleys between the double ridges that criss-cross the surface of Europa contain reddish brown deposits that also cover part of the face of Europa that is never directly exposed to Jupiter (McCord et al., 1998). This material is probably brought to the surface by the ocean water that rises to the surface through fractures in the ice crust. Accordingly, the reddish brown deposits may be composed of salts that form when the ocean water sublimates leaving a residue of *cryogenic evaporites* such as combinations of sulfates, chlorides, and hydroxides of the major metals dissolved in the water (e.g., Na, Mg, K, Ca, Fe, etc.). In addition, the cryogenic evaporites may contain biogenic organic matter provided that organisms actually live in the ocean of Europa. The surface deposits of Europa may also contain accumulations of meteoritic debris and interplanetary dust particles (IDPs).

Although the multitude of intersecting fractures and the associated double ridges have formed in response to the continuous flexing of the ice crust of Europa, the response of the underlying ocean to the fracturing of the crust is still speculative. We assume for the sake of this presentation that the ocean and the overlying ice crust of Europa have interacted with each

Figure 15.11. The surface of Europa is covered with intersecting sets of double ridges separated by narrow valleys. These ridges form as a result of tidal deformation of the crust of Europa by a process that is not yet clearly understood. The ridged terrain in this image is cut by a right lateral strike-slip fault located at 15 °N and 273 °W. The prominent ridge at the lower right is about 2.5 km wide and is one of the youngest features in this area. (Image PIA 00849, Galileo project, courtesy of NASA/JPL-Caltech/Arizona State University)

other and continue to do so at the present time. If this is true, then the double ridges and certain other surface features visible from space can be attributed to such interactions.

Although several alternative explanations for the formation of the double ridges have been proposed, none is entirely satisfactory. In general, the double ridges have been explained either as pressure ridges, like those that form in the Arctic Ocean of the Earth, or as products of cryovolcanic activity involving the forceful extrusion of geysers of ocean water through tidal cracks followed by condensation of the water vapor to form ice pellets that accumulate on both sides of the tidal fracture.

The model supported by Greenberg (2005) is a variant of the pressure-ridge model in which water rises to the “float line” of a tidal crack (i.e., about 90% of the thickness of the ice crust). The water boils and freezes in the cold vacuum of space to form a layer of porous and mechanically weak ice that may reach a thickness of about 50 cm in a matter of hours. When the crack begins to close as Europa continues in its orbit, the ice in the crack is crushed. The resulting exposure of water from below increase the thickness of the volume of crushed ice. As the crack closes, some of the crushed ice and interstitial water are squeezed out of the crack and form a single continuous ridge extending along the length of the fracture. As Europa again approaches the perijove of its orbit, the crack reopens, thereby splitting the ice ridge in such a way that deposits of the crushed and frothy ice remain on opposite sides of the crack. This process continues to build up the double-ridges until the fracture eventually becomes inactive as new fractures open elsewhere on Europa or until the crust shifts to change the orientation of the tidal fractures. Greenberg (2005) estimated that this process could form ridges that are about 1 km wide and 100 m high in less than 30,000 years. These hypothetical explanations of the formation of double-ridges need to be tested by direct observation of human observers on the ground or by means of time-lapse photography by robotic explorers.

The intersections of certain prominent fractures in Figure 15.12 provide useful points of reference for other topographic features on the surface of Europa. For example, two east-west trending fractures (*Udaeus and Minos*) intersect in the northern hemisphere of Europa (at 46.5 °N, 216 °W) and form an oblique angle between them. The *Conamara* chaos is located at 12 °N and 273 °W about 1500 km southwest of the Udaeus-Minos cross. About 1000 km south of Conamara is the site of a major impact crater called *Pwyll* (25 °S, 271 °W). A third topographic feature called the *Wedges* region (0° to 20 °S, 180° to 230 °W) is located south of the equator starting about 500 km east of a line drawn between Conamara chaos and Pwyll crater. The Wedges region occupies an area of about 1.16×10^5 km^2 in which the fractures in the crust of Europa are curved and wedge-shaped. Another cross formed by two prominent fractures occurs at 13 °N and 273 °W just north of the Conamara chaos and helps to located that important feature.

15.3.2 Impact Craters

The scarcity of impact craters has led to the conclusion that the surface of Europa is less than 50 million years olds (Zahnle et al., 2003) even though this body formed 4.6 billion years ago during the time of formation of the solar system. Most of the impact craters that did form during the long history of this body have been buried by lava flows composed of ice or have been destroyed by the breakthrough of ocean water to the surface. In addition, craters on the surface of Europa fade by creep and by sublimation of the ice exposed at the surface. The scarcity of impact craters distinguishes Europa from most other ice-covered satellites of Jupiter, Saturn, Uranus, and Neptune, although Titan (Saturn) and Triton (Neptune) also are only lightly cratered. The craters on Europa are thought to have formed primarily by impacts of comets (Zahnle et al., 2003). However, asteroids, or fragments of asteroids, could also have impacted on Europa (Greenberg, 2005, p. 268).

An important issue in the study of Europa concerns the thickness of the ice that overlies the ocean (Schenk, 2002). Some authors have concluded that the ice is "thick", whereas others maintain that it is "thin". If the ice is thick, the ocean of Europa would be isolated from the surface and topographic features such as the double ridges and chaotic terrain would be the products of the dynamics of the ice crust. In contrast, if the ice is thin, the geomorphic features on the surface of Europa are caused by interactions of the ocean and the ice crust.

The question concerning the thickness of the ice crust of Europa has been investigated by studies of the morphologies of impact craters. Some of the best preserved impact craters on the surface of Europa are identified by name in Table 15.3. Most of these are multi-ring basins (e.g., Tyre, Callanish, Tegid, and Taliesin). The crater Cilix contains a central uplift (or chaotic terrain), whereas *Pwyll* in Figure 15.13 is a recently-formed rayed crater, the ejecta of which were sprayed for more than 1000 km up to and across the Conamara chaos. The multi-ring basin named *Tyre* (33 °N, 147 W) is located on the northern hemisphere of Europa east of the Udaeus-Minos cross and close to the Minos fracture. The diameter of this spectacular feature is about 125 km, which makes Tyre one of the two largest surviving impact craters on Europa. The other one is the multi-ring basin *Callanish* (23 °N, 335 °W) which is located opposite to Tyre on the other side of Europa and the diameter of its outermost ring is similar to that of Tyre. The crater *Amergin* is interesting because its interior appears to contain chaotic terrain similar to a nearby chaos located only about 60 km southeast of the crater. Finally, the crater *Manannán* (3 °N, 240 °W) also contains hummocky terrain that closely resembles an adjacent chaos. In addition to the large impact scars listed in Table 15.3, the surface of Europa contains a large number of small bowl-shaped

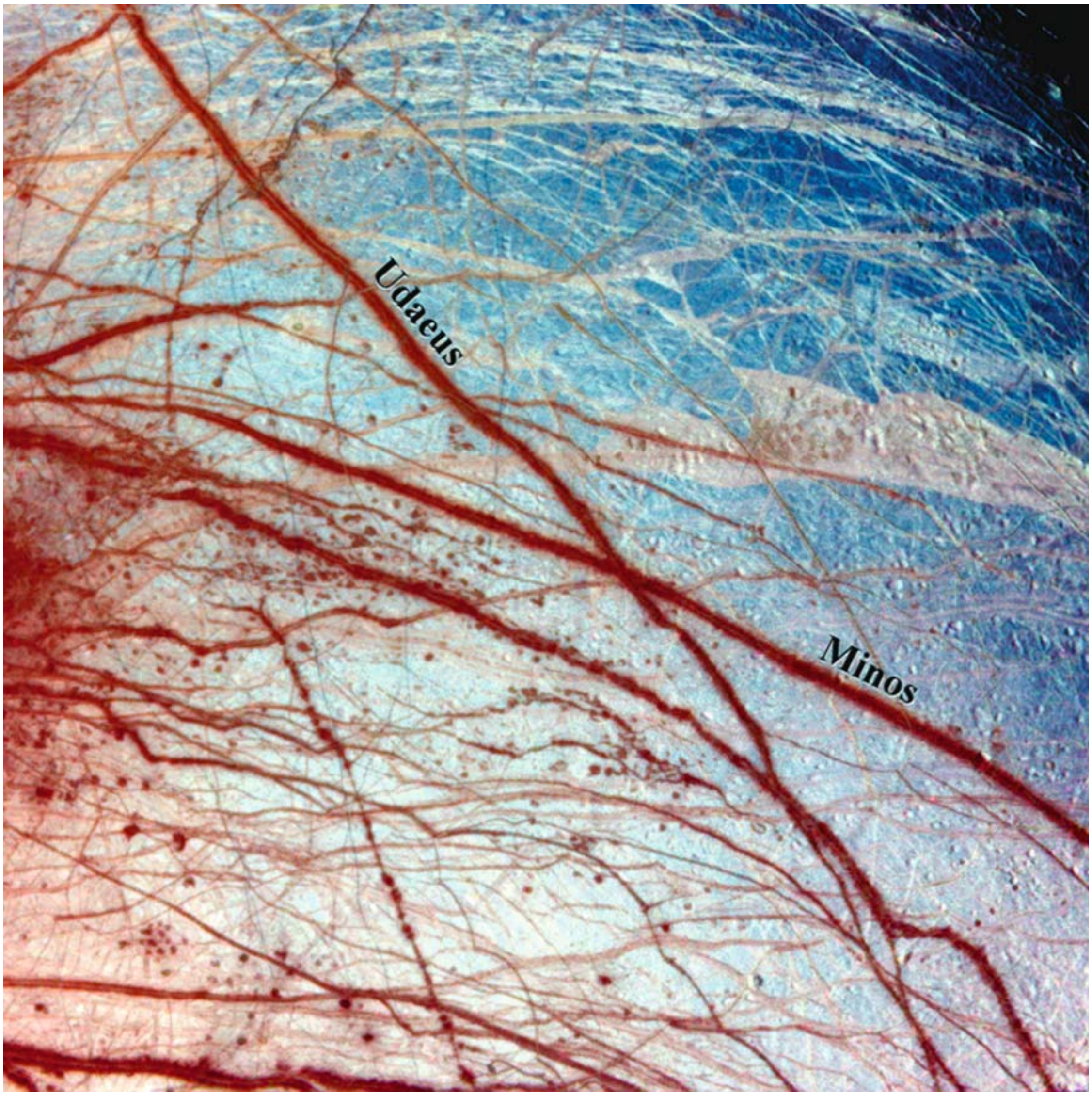

Figure 15.12. Two prominent global fractures (Udaeus and Minos) intersect in the northern hemisphere of Europa and thereby provide a prominent topographic marker. These and the other fractures in this image contain the reddish brown deposit mentioned in the caption to Figure 15.10. The color of the ice ranges from various shades of blue to nearly white based on the size of ice crystals. The region south of the Udaeus-Minos cross is covered with small brown spots or "freckles" (lenticulae). These turn out to be areas of chaotic ice when viewed at higher magnification. The surface of the ice north and south of the Minos fracture is pockmarked with small secondary impact craters that formed when blocks of ice, ejected by the impacts of meteorites and/or comets, fell back to the surface of Europa. (Image PIA 00275, Galileo project, courtesy of NASA/JPL-Caltech/University of Arizona/PIRL)

craters of secondary origin (i.e., they formed by impact of ejecta).

Chaotic terrain is not restricted to the craters Manannán and Amergin but can also be seen inside the ring basins of Tyre and Callanish. The presence of chaos implies that the large impact craters and basins actually penetrated the crust, which allowed ocean water to rise into them and to cause large rafts of crustal ice to be rotated and shifted out of their original positions until the water froze around them to form the rough-textured matrix. Another important property which the impact craters of Europa share with patches of chaotic terrain is that

Table 15.3. Impact craters on Europa (Greenberg, 2005)

Name	Location	Diameter km	Description
Pwyll	25 °S, 272 °W	24	rayed crater
Callanish	23 °S, 335 °W	~ 125	multi-ring
Tegid	1 °N, 164 °W	~ 20	multi-ring
Taliesin	?	~ 20	multi-ring
Tyre	33 °N, 147 °W	125	multi-ring
Cilix	3 °N, 182 °W	~ 50	central uplift or chaotic terrain
Manannán	3 °N, 240 °W	21	chaotic terrain
Amergin	14 °S, 230 °W	19	chaotic terrain

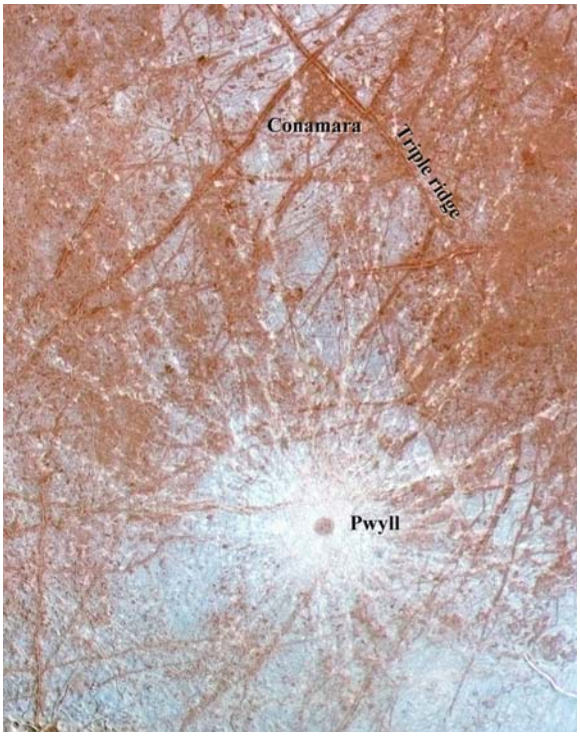

Figure 15.13. The dark spot in this image is the impact crater Pwyll. The rays of white ejecta that surround the crater overlie all older topographic features indicating that the impact that formed Pwyll occurred more recently than the local topography. The rays of ejecta appear to be composed of clean water ice and extend for more than 1000 km from the impact site up to and beyond the Conamara chaos located north of the crater and south of the cross of two prominent tidal fractures. These fractures consist of two dark parallel ridges separated by a light-colored band and are sometimes referred to as "triple ridges." The surface of the ice in this image is discolored by the reddish brown deposits and contains numerous "freckles" caused by the presence of chaotic ice. (Image PIA 01211, Galileo project, courtesy of NASA/JPL-Caltech/PIRL/University of Arizona)

they are both discolored by the presence of the reddish brown surface deposits like those that occur in the central valleys of double ridges. These deposits are attributable to the presence of ocean water at the surface, which implies that the impact craters that contain the reddish brown deposit were flooded by ocean water that entered through deep fractures that penetrated the crust.

For these and other reasons, Greenberg (2005) favored the interpretation that the ice crust of Europa is less than 30 km thick. A lower limit to the thickness of the ice crust is provided by the small bow-shaped craters having diameters less than about 5 km. These craters did not break through the ice and therefore indicate that the thickness of the crust of Europa is more than 5 km. Consequently, the study of impact craters leads to the conclusion that the thickness of the crust of Europa is more than 5 km but less than 30 km. Actually, the thickness of the crust of Europa may vary regionally depending on the amount of heat transported locally by oceanic convection currents to the underside of the crust. Therefore, the variations of the thickness of the crust of Europa may reflect the dynamics of the ocean and the amount of heat escaping locally from the silicate mantle at the bottom of the ocean.

15.3.3 Chaotic Terrains

High resolution images obtained during flybys of the spacecraft Galileo reveal that areas of chaotic terrain are a common geomorphic feature on the surface of Europa. The areas consisting of chaos range in area from about 12, 800 km^2 (80 × 160 km) for *Conamara* (Figure 15.14) to small reddish-brown spots called *lenticulae* (freckles) or *maculae* (Figure 15.12). The designation of small reddish brown spots on the surface of Europa as lenticulae or maculae originated at a time when only low-resolution images were available. High-resolution images of these spots obtained more recently by the spacecraft Galileo reveal that the reddish brown spots consists of chaotic terrain that is not adequately described by names that make sense only at low resolution. All of the examples of chaotic terrain are discolored presumably because they contain the reddish brown deposits that indicate the former presence of ocean water on the surface (Section 15.3.1),

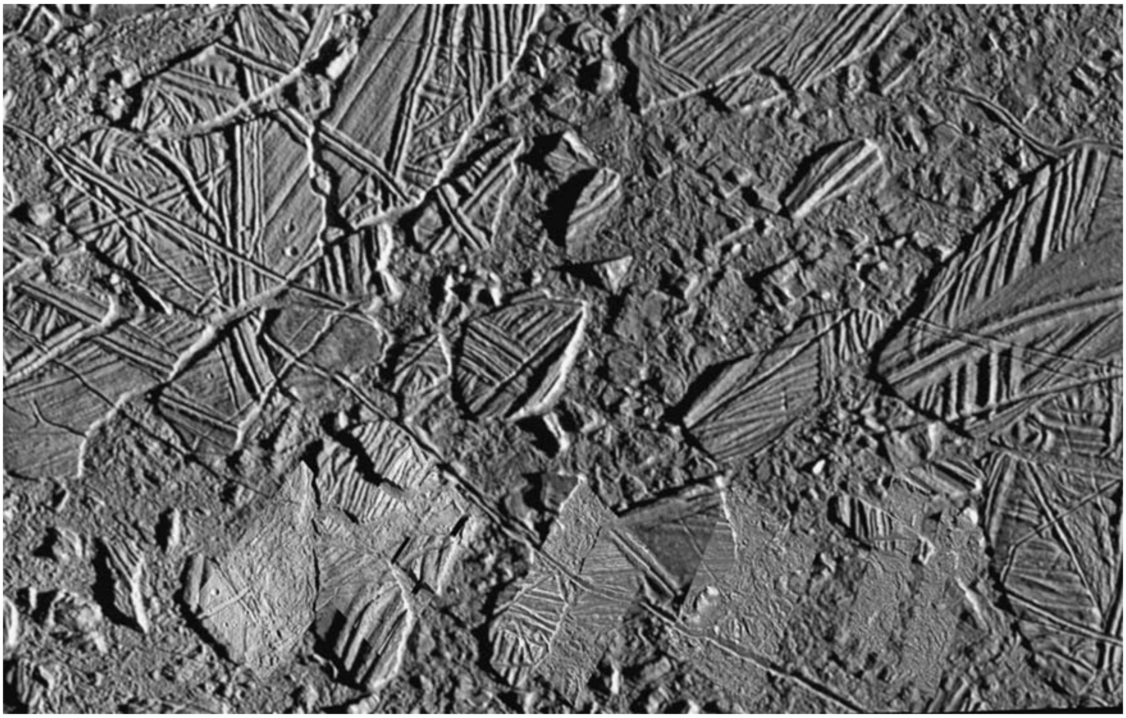

Figure 15.14. The Conamara chaos covers an area of about 35 × 50 km centered on 9 °N and 274 °W (Figure 15.13). It consists of angular blocks of ridged ice that are imbedded in hummocky ice. Several of the blocks (icebergs) have been rotated while others have been displaced from the surrounding crustal ice by widening fractures. Reconstructions of the Conamara chaos demonstrate that much ice evaporated during the formation of this feature. (Image PIA 01403, Galileo project, courtesy of NASA/JPL-Caltech/Arizona State University)

either as a result of melt-through from below or as a result of break-through from above. After a chaotic terrain (e.g, Conemara) or a large impact crater (e.g., Callanish) solidified by freezing of the extruded ocean water, tidal cracks cut through or around the remaining rafts of the original surface because tidal cracks form continuously, even at the present time, whereas melt-throughs and break-throughs occur episodically.

Examples of chaotic terrain typically contain angular blocks of ridged ice that have been displaced and rotated relative to adjacent blocks. These "icebergs" are surrounded by rubbly ice that contains smaller chunks of "brash ice" in a frozen matrix that formed when exposed ocean water boiled and froze in the cold vacuum of space. The Conamara chaos in Figure 15.14 has been partially reconstructed by re-aligning blocks of ice by means of prominent double ridges and by fitting their shapes together like pieces of a jigsaw puzzle. The reconstructions recreate part of the previously existing surface but also demonstrate that much crustal ice was crushed or vaporized such that large gaps remain (e.g., Figure 15.1b and 16.3 of Greenberg, 2005). Two other noteworthy examples of chaotic terrain are *Thera* (47 °S, 181 °W) and *Thrace* (41° to 48 °S, 170° to 175 °W).

The origin of chaotic terrain has been variously attributed to:

1. Upwelling of ice diapirs with diameters of about 10 km from within a "thick" crust.
2. Extrusion of water-ice slurries through the crust to form dome-shaped lobate deposits on the surface (e.g., the *Mitten*).
3. Local melting of "thin" crust of ice by rising plumes of comparatively warm water of the underlying ocean.

Although each of the three hypotheses has been advocated by certain groups of investigators, the third alternative illustrated in Figure 15.15 requires the smallest number of special assumptions and therefore seems capable of explaining the formation of chaotic topography on Europa in the most plausible way.

The melt-through hypothesis relies on the reasonable assumptions that the ice crust of Europa is "thin" (i.e., < 30 km as indicated by crater morphology), that plumes of "warm" water form in the ocean as a result of heat emanating locally from the silicate mantle at the bottom of the ocean (e.g., by hotsprings that discharge ocean water circulating through the upper mantle), and that the ice crust is in buoyant equilibrium with the ocean (i.e., the water in the ocean is not pressurized). The panels (a to e) of Figure 15.15 illustrate the stages of a hypothetical process as result of which chaotic terrain on the surface of Europa can form by melt-through of the ice crust from below . In addition, panels d and e demonstrate that icebergs can break off the edges of the meltwater pool and drift away from their original sites as the water boils and freezes into the rubbly matrix that characterizes chaotic terrain on Europa (e.g., Conamara, the Mitten, Thera, Thrace, and many other examples).

The process of chaos formation by melt-through can also take place in modified form when the ice crust of Europa is fractured locally by the impact of a comet or asteroid. In this case, the resulting impact cavity would fill with ocean water up to the floatline (Figure 15.5c). Rafts of surface ice as well as fragments of crushed ice would drift in the pool until the boiling water freezes around them to form the chaotic surface that is revealed in high-resolution images of impact basins (e.g., Tyre and Callanish). Note that the heat released by an impact on the surface of Europa cannot cause the ice to melt because the ambient pressure is far below the triple point of water (Figure 12.5). Therefore, the ice in the target area is vaporized and the resulting water vapor may either drift away into interplanetary space or recondenses in the form of snowflakes or ice pellets that are then deposited on the surface surrounding the impact site.

The hypothesis that the chaotic terrain is the result of convection of warm ice assumes that the crust of Europa is more than 30 km thick. This

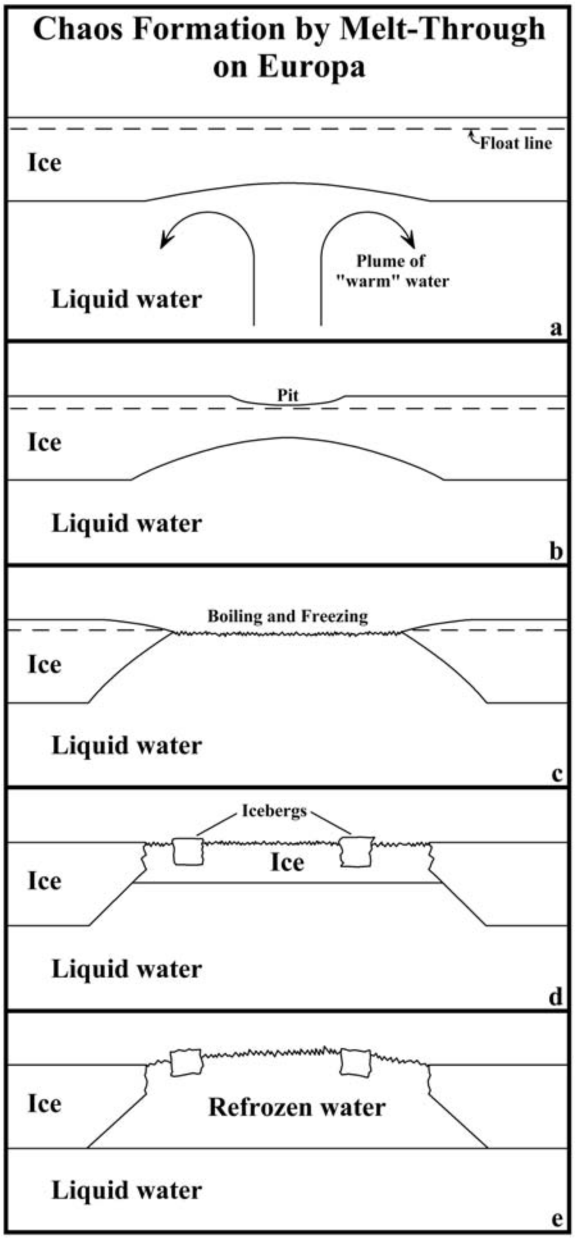

Figure 15.15. a. A plume of "warm" water rises from the bottom of the ocean of Europa and begins to melt the underside of the ice crust above it. The float line is the level to which water rises if the ice crust is in buoyant equilibrium with the underlying ocean. b. Continued melting forms a large cavity on the underside of the ice crust and causes a shallow pit to form on the surface c. The melt cavity expands to the surface and liquid ocean-water boils and freezes to form a thin layer of rubbly matrix ice d. Icebergs break off from the edge of the ice and float in the water as the boiling water freezes around them e. When the plume of warm water subsides, the water that filled the melt cavity in the ice crust refreezes. The surface displays the characteristic properties of chaotic terrain and bulges slightly to accommodate the increase in volume of the refrozen water. Adapted from Figures 16.13 and 16.14 of Greenberg (2005). Not drawn to scale

assumption is not consistent with the morphology of impact craters. The alternative hypothesis that lava composed of water is erupted onto the surface of Europa requires that the ocean is pressurized, perhaps by the tidal distortion of its shape. In that case, the daily opening and closing of tidal fractures should cause cryovolcanic activity in the form of geysers and other kinds of eruptions, but none have been seen in the images of the surface of Europa. Nevertheless, localized melting of the ice crust by warm water can be viewed as a cryovolcanic process in the sense that the warm water that melts the overlying crust is analogous to silicate magma on the Earth intruding the solid crust composed of rocks. When the water (magma) reaches the surface, it cools and freezes (crystallizes) to form solid ice (monomineralic rock). As a result of the exposure of liquid water at the surface, heat from the interior of Europa escapes into space thereby helping to maintain thermal equilibrium.

15.3.4 Life in the Ocean

The view that is emerging from the study of Europa is that it has a thin ice crust ($\sim 10\,\text{km}$) which covers a global ocean of liquid water containing dissolved salts. The temperature of the water at the base of the crust depends on the salinity of the water which determines its freezing temperature. For example, seawater on the Earth generally freezes at $-2.2\,^{\circ}\text{C}$. The temperature of the water probably increases with depth, especially close to the bottom of the ocean. The underlying silicate mantle is likely to be a source of heat that locally warms the bottom water, especially where ocean water that has circulated through the upper mantle is discharged by hotsprings. More vigorous volcanic activity, such as eruptions of silicate lava and hot gases, is not indicated by any evidence visible at the surface of Europa. Regardless of whether the crust of Europa is "thick " or "thin", the amount of sunlight that reaches the ocean is very small, except perhaps in the vicinity of melt-throughs or where strike-slip faulting is occurring along tidal fractures (e.g., *Astypalaea* linea, Greenberg 2005, Chapter 12). The ice in these areas is likely to be thin and therefore may allow more sunlight to enter the ocean.

In summary, the ocean of Europa can be described by certain of its properties that can be postulated by reasonable interpretations of existing observations:

1. The ocean consists of liquid water.
2. The water contains salts of common elements derived by chemical weathering of the silicate, oxide, and sulfide minerals in the underlying mantle.
3. The temperature of the water increases with depth and is everywhere above the freezing point of the salty water in the ocean.
4. Heat is entering the ocean through the bottom, perhaps by discharge of hotsprings. Eruption of lava and hot gases is not indicated by presently available evidence.
5. Very little, if any, sunlight enters the ocean except under special short-lived circumstances.
6. Carbon compounds such as carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), and complex organic molecules are assumed to be present in the water because of their occurrence in the solar nebula.
7. Minerals whose surfaces contain electrically charged sites exist in the sediment at the bottom of the ocean and in suspension.
8. The water in the ocean is continually stirred by tidal deformation and by thermal convection.

The environmental conditions described above are thought to be favorable for the development of life, although the process by means of which self-replicating cells form is not understood. Nevertheless, these favorable conditions have existed in the ocean of Europa ever since its interior differentiated, and these conditions have remained stable without significant disruption for more than four billion years right up to the present time. Evidently, the environment in the ocean of Europa has been conducive to life for a much longer time than the environment on the surface of Mars (Section 12.8). Even if living organisms did once exist on Mars, there was hardly enough time for evolution to diversify these organisms before increasing aridity and decreasing global temperature caused their extinction or forced them into a long-lasting state of hibernation.

The environmental conditions in the ocean of Europa are at least as favorable to life as the conditions in the primordial ocean of the Earth where life did originate and did evolve in spite of episodes of catastrophic impacts and climate fluctuations (e.g., global glaciations). Therefore, the ocean of Europa may be inhabited by living organisms that have diversified by evolution in order to take advantage of different habitats available to them. Although this prediction is not unreasonable, the existence of life in the ocean of Europa must be confirmed by landing a robotic spacecraft on its surface. Even the reddish brown material that has accumulated on the surface may contain evidence concerning life in the ocean of Europa.

If a future mission to Europa is undertaken, great care will be required to assure that Europa is not contaminated by terrestrial bacteria and viruses that may cause a pandemic among any indigenous organism that may be present in the ocean. Similarly, if any samples from Europa are to be returned to Earth, such materials must be quarantined to prevent alien organisms from infecting humans and/or the rest of the terrestrial biosphere (Sagan and Coleman, 1965; NRC, 2000; Greenberg and Tufts, 2001).

15.3.5 Summary

Europa is the smallest of the Galilean satellites and differs from Io by having an ice crust that covers an ocean of salty water. In addition, Europa has a magnetic field that is induced by electrical currents which arise in the ocean as a result of interactions with the magnetic field of Jupiter. Like Io, Europa is heated by tidal friction caused by the deformation of its shape as it revolves around the Jupiter. The amount of heat released has prevented the water in the ocean from freezing, but is not sufficient to cause volcanic activity.

The ice crust of Europa is virtually covered by intersecting double ridges separated by median valleys that occupy the sites of deep fractures caused by tidal stress. These fractures contain a record of the tidal tectonics that has affected the crust of Europa throughout its history. The double ridges form by freezing of ocean water that rises into the tidal fractures as they open and close at regular intervals.

The surface of Europa is partly covered by reddish brown deposits composed to salts of the major elements that are dissolved in the ocean water. Therefore, the presence of these cryogenic evaporites implies that ocean water does reach the surface of Europa. In addition, the salt deposits may contain organic matter related to the presence of living organisms in the ocean.

Europa has only a small number of impact craters on its surface because they are covered up or destroyed by the continuing geological activity. The largest craters, Tyre and Callanish, are both multi-ring basins about 250 km in diameter. The interiors of most craters with diameters of 20 km or more indicate that ocean water rose into them from below and floated blocks of ice from the rims and floors of the craters thereby creating chaotic terrain. The morphology of the impact craters indicates that the thickness of the crust is about 10 km on average.

Areas of chaotic terrain, ranging in diameter from 160 km (Conamara) to less than 10 km, are widely distributed over the surface of Europa. All of these areas consist of rafts of crustal ice that have been dislodged and rotated by floating in ocean water. In addition, the rubbly ice that surrounds the icebergs is discolored by reddish brown salt deposits, which caused small brown spots on the surface to be referred to as lenticulae (freckles) or maculae (reddish yellow body in the center of the retina) in low-resolution images.

The most plausible explanation for the origin of chaotic terrain is by melt-through of the ice crust by plumes of warm water rising from the floor of the ocean. The end result is that ice-free areas form on the surface of Europa where ocean water is exposed to the cold vacuum of space for short periods of time. The water boils as it freezes to form the matrix of rubbly ice that is characteristic of chaotic terrain.

The environmental conditions in the ocean of Europa permit aquatic life to exist. In addition, these conditions have probably remained stable for about four billion years, which may have allowed these organisms to diversify by evolution to take advantage of all existing habitats. The possibility that the ocean of Europa is inhabited will be investigated in the future by landing one or several robotic spacecraft on its surface. Great care will be required to sterilize the landers and to avoid contaminating the Earth with alien organism that could harm terrestrial plants and animals.

15.4 Ganymede in the Middle

Ganymede, the Galilean satellite, has properties that are intermediate between those of active Europa and those of inactive Callisto. It has the distinction of being the largest of the Galilean satellites in Table 15.1 in terms of volume and mass. In fact, Ganymede is larger than the planets Mercury and Pluto but does not quite measure up to Mars. Among the numerous satellites of Jupiter, Saturn, Uranus, and Neptune only Titan comes close to the volume and mass of Ganymede. . These comparisons drive home the point that Ganymede is a world that is not to be overlooked among the many satellites of the giant planets.

15.4.1 Ice Crust

The images of Ganymede in Figure 15.16 reveals the presence of areas of dark and heavily cratered ice that appear to have been disrupted by bands of light-colored grooved ice. Crater counts confirm that the dark surface is older than four billion years and that the light-colored bands are younger than the dark areas, but nevertheless have exposure ages of the same order of magnitude (Hartmann, 2005, p. 263). The largest area of dark ice, called *Galileo regio*, has a diameter of about 3200 km. Other large areas of dark ice are *Marius* regio, *Perrine* regio, *Barnard* regio, and *Nicholson* regio. Dark ice also occurs in smaller angular areas scattered over the surface of Ganymede. In Figure 15.16 dark ice is cut by narrow bands of the younger light-colored ice that either forced the fragments of old ice to move apart or, more likely, were superimposed on the dark ice. In a global view of Ganymede, the dark areas are the remnants of the original crust that was broken up or rejuvenated, leaving angular remnants of the old ice separated by bands of younger ice.

The diameters of the impact craters that occur both on the dark and the light-colored surfaces of Ganymede range from less than 5 km to more than 100 km. Small craters (5 to 20 km) have central uplifts, raised rims, and recognizable ejecta blankets. Larger craters (20 to 100 km) have a central pit that may be characteristic of craters formed by impacts into the ice crust of Ganymede. Craters having diameters of more than 60 km contain a dome within the central pit. The largest craters have relaxed their original shapes as a result of the creep of the ice. For this reason, they have been called "*palimpsests*" defined as "a reused writing surface on which the original text has been erased" (Hartmann, 2005, p. 302). Large craters having diameters of 100 km relax in about 30 million years, whereas 10-km craters require 30 billion years. The craters that formed by recent impacts on dark as well as light-colored surfaces are surrounded by light-colored and rayed ejecta blankets. This observation is confirmed by the image of Khensu crater in Figure 15.17, which indicates that the dark surfaces on Ganymede have formed on crustal ice that was originally light-colored. The darkening of the ice with increasing exposure age is attributable to the accumulation of sediment such as meteorite debris and interplanetary dust, refractory particles released by sublimation of the crustal ice, and carbon residue derived by decomposition of carbon-bearing compounds by cosmic rays, the solar wind, and ultraviolet light (Section 15.1a).

The large palimpsests on Ganymede are multi-ring basins with diameters of several hundred kilometers (e.g., *Memphis* facula, 350 km). (The word "facula" is also used to describe bright granular structures in the photosphere of the Sun). The large impactors that formed these basins did not break through the ice crust of Ganymede as they did on Europa. Therefore, the ice crust of Ganymede is considerably thicker than the crust of Europa, presumably because the tides of Jupiter generate less heat on Ganymede than they do on Europa. Another indication that Ganymede has a thicker crust than Europa is the absence on Ganymede of chaotic terrain and of the reddish brown salt deposits (Pappalardo, 1999). In addition, Ganymede does not have active or inactive volcanoes, plumes of gas, or geysers of boiling water.

15.4.2 Rejuvenation

The existence of the bright areas implies that parts of the surface of Ganymede were rejuvenated a few hundred million years after its accretion and internal differentiation. The question is: How did it happen? The light-colored bands of ice in Figure 15.18 contain sets of

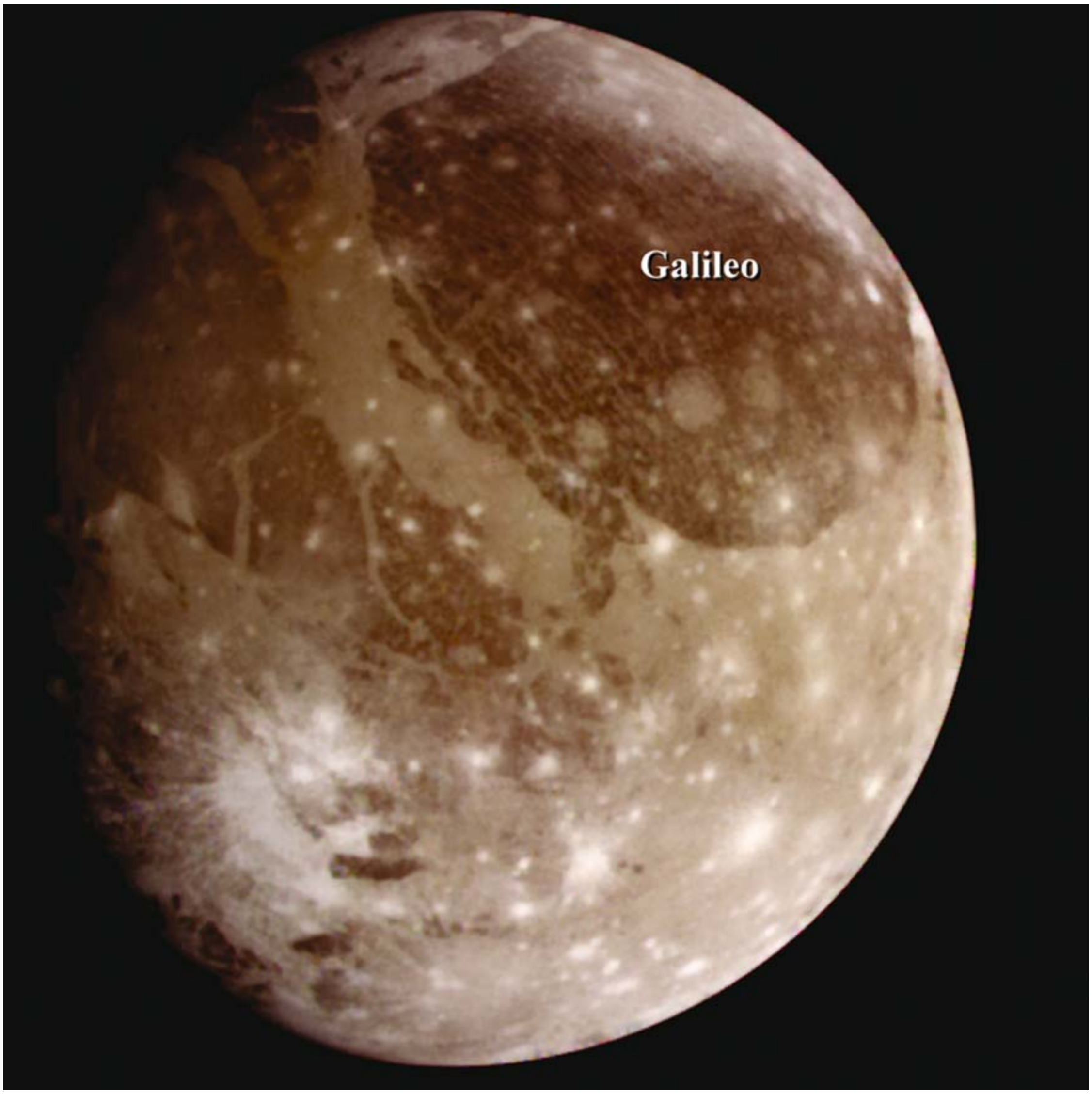

Figure 15.16. Ganymede, the largest Galilean satellite, has a thick crust composed of water ice. The crust contains areas of dark-colored and heavily cratered ice (e.g., Galileo) in contact with areas of light-colored ice that separate what appear to be remnants of the older dark-colored crust. Numerous bright spots in this image are recently-formed impact craters and the associated ejecta. Even though Ganymede is the largest and most massive satellite in the solar system, it does not have an atmosphere and it is no longer geologically active. (Image PIA 00716, Galileo project, courtesy of NASA/JPL-Caltech)

parallel ridges and valleys giving the appearance that the terrain is "grooved". The valleys between the ridges differ from those on Europa because they do not appear to be presently active tidal fractures. Instead, the sets of ridges and valleys on Ganymede may be normal faults (i.e., horsts and grabens) or tilted blocks of the ice crust containing parallel normal faults that are differentially eroded to form the valley-and-ridge topography (Pappalardo, 1999).

Images returned by the Voyagers and by Galileo show that bands of grooved terrain cut across other bands thereby establishing a time series based on the principle of cross-cutting relationships. Some of the bands of grooved terrain of Ganymede are also cut by strike-slip faults. The evident structural complexity of the grooved terrain suggests that it formed during an episode of violent deformation of the ice crust in the early history of Ganymede. The results

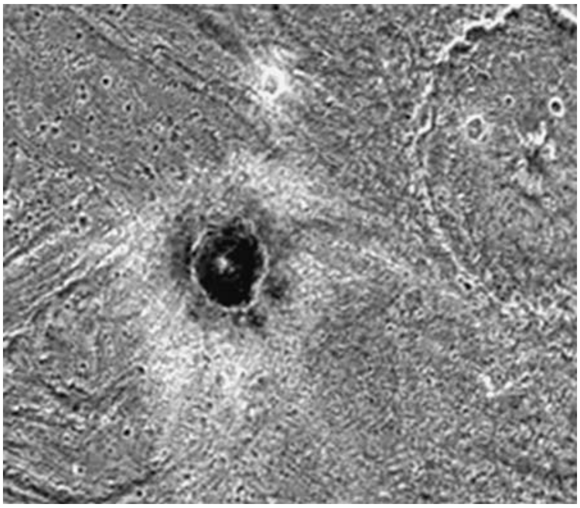

Figure 15.17. The impact crater Khenzu, located at 2 °N and 153 °W on Ganymede, has a diameter of about 13 km. The surrounding terrain is part of the light-colored Uruk sulcus. The crater has a central uplift projecting upward from a dark floor. Nevertheless, the ejecta blanket consists of white (i.e., clean) ice indicating that the surface of the ice crust of Ganymede has darkened with age. The dark material covering the floor of Khenzu may be a residue of the meteorite that formed the crater. A second crater named El appears in the upper right corner of the image. This crater (diameter = 54 km) is older than Khenzu and has a small pit in the center. Such pits are characteristic of some impact craters on Ganymede. (Image PIA 01090, Galileo project, courtesy of NASA/JPL-Caltech/Brown University)

of the deformation may have been enhanced by the thermal gradient within the thick ice layer. Warm ice at depth could have been soft and plastic, whereas the cold ice at the surface was hart and brittle. Consequently, warm ice from the "lower" crust could have been extruded through the brittle "upper" crust, thereby giving rise to a kind of cryovolcanic activity. However, the available images of Ganymede do not show much evidence of recent cryovolcanic activity (Pappalardo, 1999).

15.4.3 A Conjecture

An alternative explanation for the origin of the grooved terrain on the surface of Ganymede arises from the observation by the Galileo spacecraft that Ganymede has a weak internally-generated magnetic field. According to the theory of the self-exciting dynamo (Section 6.4.5), planetary magnetic fields require the presence of an electrically conducting fluid which must be stirred by thermal convection and/or by the rotation of the body (e.g., metallic hydrogen in Jupiter). Therefore, the existence of a magnetic field implies either that Ganymede has a molten iron-rich core like the Earth or that a layer of salty water exists beneath its ice crust as in the case of Europa (Figure 15.3). If the magnetic field of Ganymede is actually generated within a layer of salty water, then its crust could have been rejuvenated by the extrusion of ice that formed by freezing of water in tidal fractures as appears to be happening on Europa even at the present time. In order for this process to work on Ganymede, its crust must have been significantly thinner in the past than it is at the present time.

The thickness of the ice crust of Ganymede may have been thinner during its early history (i.e., before four billion years ago) because of the presence of excess heat in its interior arising from compression and the decay of radioactive atoms. The resulting high rate of heat flow caused the crust to be thinner and the layer of water to be thicker than they are at the present time. Consequently, the rejuvenation of the surface of Ganymede occurred during its early history but it gradually ended as the water began to freeze to the underside of the crust causing it to thicken until all geological activity was suppressed. The present thickness of the crust of Ganymede may correspond to the amount of heat that continues to be generated by tidal friction. Accordingly, Ganymede has a thicker ice crust than Europa because the tides of Jupiter are generating less heat in Ganymede than they generate in Europa. The geological histories of the individual Galilean satellites depend primarily on the amounts of tidal heat that are generated within them. The effectiveness of the tides to generate heat in the Galilean satellites decreases with increasing distance from Jupiter. Hence, Ganymede is the satellite in the middle: less active than Europa but more active than Callisto.

15.4.4 Summary

Ganymede is the largest satellite in the solar system exceeding even the planets Mercury and Pluto in volume and mass. Its ice crust contains large remnants of an original crust whose surface

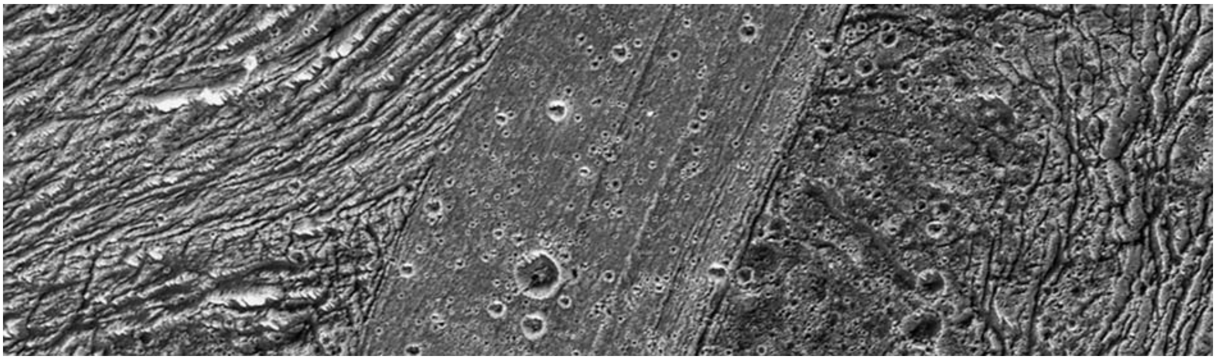

Figure 15.18. Close-up of the surface of Ganymede showing a band of light-colored and grooved ice traversing older and highly corrugated ice. The grooved band is a product of rejuvenation of the surface of Ganymede during an early period in its history when it contained more heat than it does at present. The ejecta deposits of the impact craters in this image have darkened with age. Although the grooved terrain of Ganymede shows some resemblance to the intersecting ridges of Europa, the origin of the topography of Ganymede is not yet understood (Image PIA 02572, Galileo project, courtesy of NASA/JPL-Caltech/DLR (Berlin and Brown University)

has darkened with age, which distinguishes these remnants from younger rejuvenated areas that have a light-colored surface.

Both kinds of surfaces bear the scars of impacts by comets and small asteroids that have left a record of craters ranging in diameter from less than 5 km to more than 100 km. The most recent craters in the dark areas are surrounded by light-colored ejecta blankets indicating that the ice itself is white and clean and that the surface of the dark areas is covered by sediment such as meteorite debris, interplanetary dust, residual sublimation products, and carbon-rich residues that have accumulated for close to 4.6 billion years (Section 15.1). These kinds of deposits are less evident in the light-colored areas because they have been exposed for a shorter interval of time.

The light-colored areas are heavily grooved by sets of parallel ridges separated by valleys. The bands of grooved ice intersect and cross-cut each other indicating that they formed sequentially. The valley-and-ridge topography does not appear to be forming at the present time, presumably because the ice crust of Ganymede has become too thick to be fractured by tides raised by Jupiter. The exposure age of the grooved terrain indicates that it formed a few hundred million years after the accretion and internal differentiation of Ganymede at a time when its ice crust may have been thinner.

The presence of a layer of salty water beneath the crust is suggested by the fact that Ganymede has a weak internally-generated magnetic field. At the time when the grooved terrain rejuvenated parts of the ancient crust, the layer of liquid water may have been thicker and the overlying crust may have been correspondingly thinner than they are at the present time. According to this conjecture, the crust began to thicken when the original ocean started to freeze as Ganymede cooled until its internal heat declined to the level sustained by tidal friction.

15.5 Callisto, Left Out in the Cold

Callisto was a princess who was seduced by Zeus, the chief God of Greek mythology. His wife punished Zeus for his infidelity by transforming Callisto into a bear. Years later, Zeus placed Callisto among the stars as the constellation Ursa Major (Big Dipper, Figure 2.2) and her son Arcas became Ursa Minor (Little Dipper). However, Hera arranged that Ursa Major could never bathe in the water of the Mediterranean Sea (Section 2.1). This tale illustrates the way in which the mythology of the Greeks explained why the constellation Ursa Major is visible in the sky at night from all parts of the Mediterranean region and can therefore be used for navigation by identifying the position of the pole star (Houtzager, 2003).

15.5.1 Physical Properties

The Galilean satellite Callisto in Figure 15.19 does not participate in the orbital resonances and jovian tides that have been so important in the evolution of the other satellites in this group (Section 15.1.2). Callisto is excluded from these phenomena because of the great distance between it and Jupiter (1884×10^3 km). In other words, Callisto was left out in the cold of interplanetary space. Callisto is almost twice as far from Jupiter as Ganymede and almost five times farther than Io (Table 15.1). Its period of revolution (16.689d) is more than

Figure 15.19. Callisto is so far removed from Jupiter that it is not heated by tidal friction and has cooled without interruption since it formed 4.6 billion years ago. As a result, the surface of Callisto is densely covered by impact craters and its interior is undifferentiated (i.e., Callisto lacks a core). As in the case of Ganymede, the surface of Callisto is covered by dark-colored deposits that consist of a mixture of meteorite debris, interplanetary dust particles, and organic matter that has formed by polymerization of methane that was imbedded in the ice. The light-colored ejecta of recent impact craters confirm that the ice beneath the dark surface of Callisto is clean water ice. (Image PIA 03456, Galileo project, courtesy of NASA/JPL/Caltech/DLR, Germany)

two times longer than the period of Ganymede (7.155 d) and almost ten times longer than the period of revolution of Io (1.769d). The diameter of Callisto (4840 km) is smaller than that of Ganymede (5280 km) but larger than those of Io (3630 km) and Europa (3130 km). Callisto has the lowest bulk density (1.790 g/cm^3) of the Galilean satellites (Figure 15.1) and is composed of an undifferentiated mixture of water ice (density $\sim$ 1.00 g/cm^3) and refractory silicate and oxide particles (density $\sim$ 3.00 g/cm^3). Accordingly, the body of Callisto consists of about 60% ice by volume and 40% refractory particles (Science Brief 15.6.2). Callisto is undifferentiated because the tides of Jupiter, the impacts of planetesimals at the time of accretion, and the decay of radioactive atoms did not release enough heat to cause the ice to separate from the rocky component in its interior.

The surface of Callisto consists of water ice overlain in most places by sediment similar in composition to that which covers the dark areas of Ganymede (Section 15.4.1). However, the low albedo of Callisto (17%) compared to that of Ganymede (43%) indicates that the layer of sediment on the surface of Callisto is probably thicker and more continuous than the sediment layer on the surface of Ganymede. The low albedo of Callisto also indicates that the surface has not been rejuvenated, which means that Callisto has not been active even during its earliest history.

15.5.2 Impact Craters

The absence of cryovolcanism or internal tectonic activity has allowed impact craters to be preserved on the surface of Callisto including large multi-ring basins. The crater density in Figure 15.20 is at saturation, which means that the exposure age of the surface is close to 4.6×10^9 year (Hartmann, 2005). The largest crater on Callisto is a multi-ring basin called *Valhalla* (Science Brief 15.6.3). It consists of a central impact site that is surrounded by a large number of rings spaced about 50 km apart. The rings consist of undulations in the surface formed by energy spreading outward from the impact site with a maximum radius of about 1500 km. The central crater of Valhalla, located at 11 °N, 58 °W (Beatty and Chaikin, 1990), is a palimpsest because it was partially erased by plastic flow of the ice which filled the original impact cavity and thereby restored the curvature of Callisto. The center of Valhalla is a light-colored area having a diameter of about 600 km where comparatively clean ice is exposed. A second multi-ring basin in Figure 15.21, located at about 30 °N and 140 °W, called *Asgard* (Science Brief 15.6.3) has only about one half the diameter of Valhalla but is better preserved.

The color of ejecta blankets that surround recent impacts is white, which confirms that the ice in the outermost crust of Callisto does not contain enough dust particles to darken its color. However, the ice of Callisto, as well as the ice of Europa and Ganymede, may contain carbon-bearing gases including carbon dioxide and methane.

15.5.3 Differential Sublimation

The surface of Callisto contains isolated pinnacles in smooth areas of ice. The resulting knobby landscape in Figure 15.22 appears to be a product of differential sublimation of ice that contains impurities which locally retard the rate of sublimation. The existence of this landscape implies that sublimation of ice is a more effective weathering agent on Callisto than it seems to be on Europa and Ganymede.

When ice is exposed to a vacuum at a temperature close to, but less than, the freezing point of water, the ice sublimates rapidly and leaves behind a residue of the particles and salts it contained. This process, known as freeze drying, is used in industry to remove water, as for example in the manufacture of "instant" coffee. However, the rate of sublimation of ice in a vacuum decreases with decreasing temperature and becomes ineffective at the low temperatures that prevail on the ice-covered satellites of the outer planets. This explains why these ice-covered satellites have survived for billions of years without losing their ice crusts.

Differential weathering of ice by sublimation may be more effective on Callisto than on Europa because the maximum measured noontime temperature of Callisto is 28° warmer than on Europa (i.e., Callisto: −120 °C.; Europa: −148 °C; Hartmann, 2005). The reason for the comparatively high surface temperature of

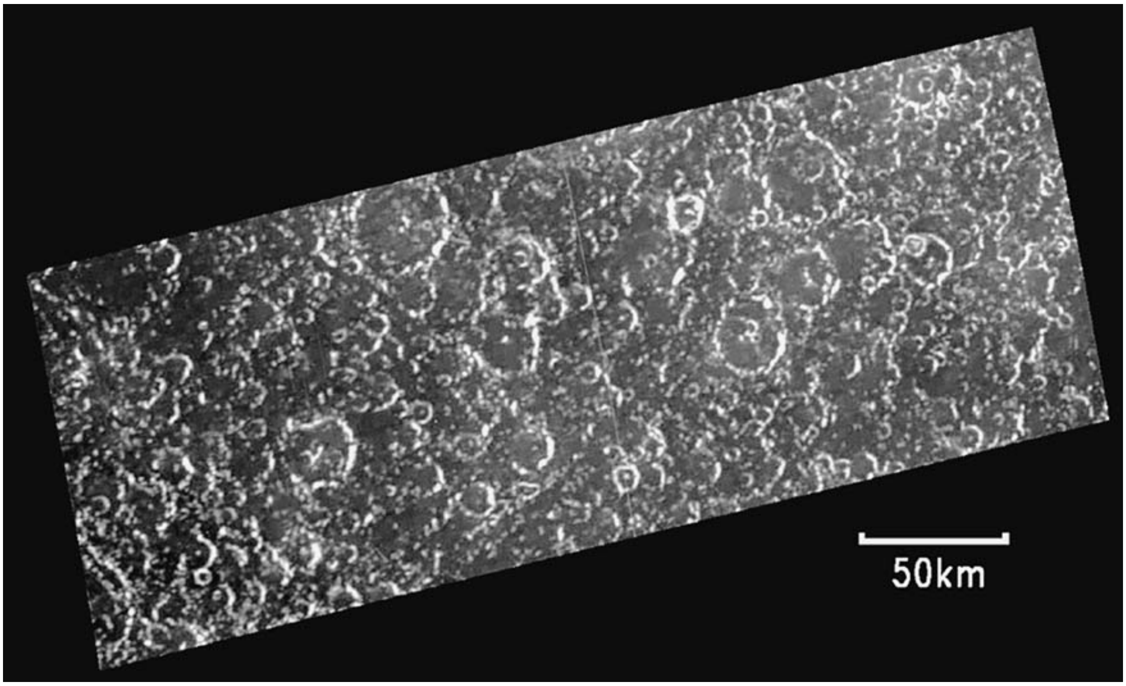

Figure 15.20. The surface of Callisto is completely covered by impact craters packed "shoulder-to shoulder." The area shown here is antipodal to the giant impact crater Valhalla. Nevertheless, the expected hummocky or ridged terrain is *absent*, which implies that the seismic energy from the Valhalla impact was absorbed in the interior of Callisto. This evidence favors the view that Callisto contains liquid water in its interior. A similar conjecture arises from measurements of the magnetic field of Jupiter in the vicinity of Callisto. However, the hypothesis that liquid water is present in the interior of Callisto (and Ganymede) requires confirmation (Image PIA 02593, Galileo project, courtesy of NASA/JPL-Caltech/University of Arizona/HiRise-LPL)

Callisto is that it absorbs more sunlight than Europa (i.e., the albedo of Callisto is lower than that of Europa). The rate at which ice is lost from the surface of Callisto may also be affected locally by the thickness of sediment that covers it. As a result, residual ridges and pinnacles form where the sublimation of ice is retarded. In addition, small impact craters on the surface of Callisto may be erased by sublimation of the ice.

15.5.4 Summary

The gravitational interactions of Callisto with the spacecraft Galileo indicate that the most remote of the Galilean satellites did *not* differentiate internally into a dense iron-rich core, a silicate mantle, and an ice crust. The failure to differentiate tells us that Callisto was not heated sufficiently to allow dense materials (i.e., silicates, oxides, and grains of metallic iron) to sink toward the center thereby concentrating water ice into an outer shell like the ice crusts of Europa and Ganymede.

One of several reasons why Callisto remained cool is that tidal heating is ineffective because of the great distance between Jupiter and the orbit of Callisto. In addition, Callisto apparently accreted from small particles of ice and dust whose impact did not release enough heat to melt the ice. The other Galilean satellites may have formed similarly without melting and their internal differentiation may have been caused primarily by heat generated by the tides of Jupiter rather than by the impacts of planetesimals or by the decay of radioactive atoms. Nevertheless, after Callisto had accreted without melting, it was hit by comets and asteroids which saturated its surface with craters.

The diameters of craters on the surface of Callisto range from about one to several hundred kilometers. The largest impact crater is the Valhalla multi-ring basin. The rings that surround the impact site are undulations in the surface of

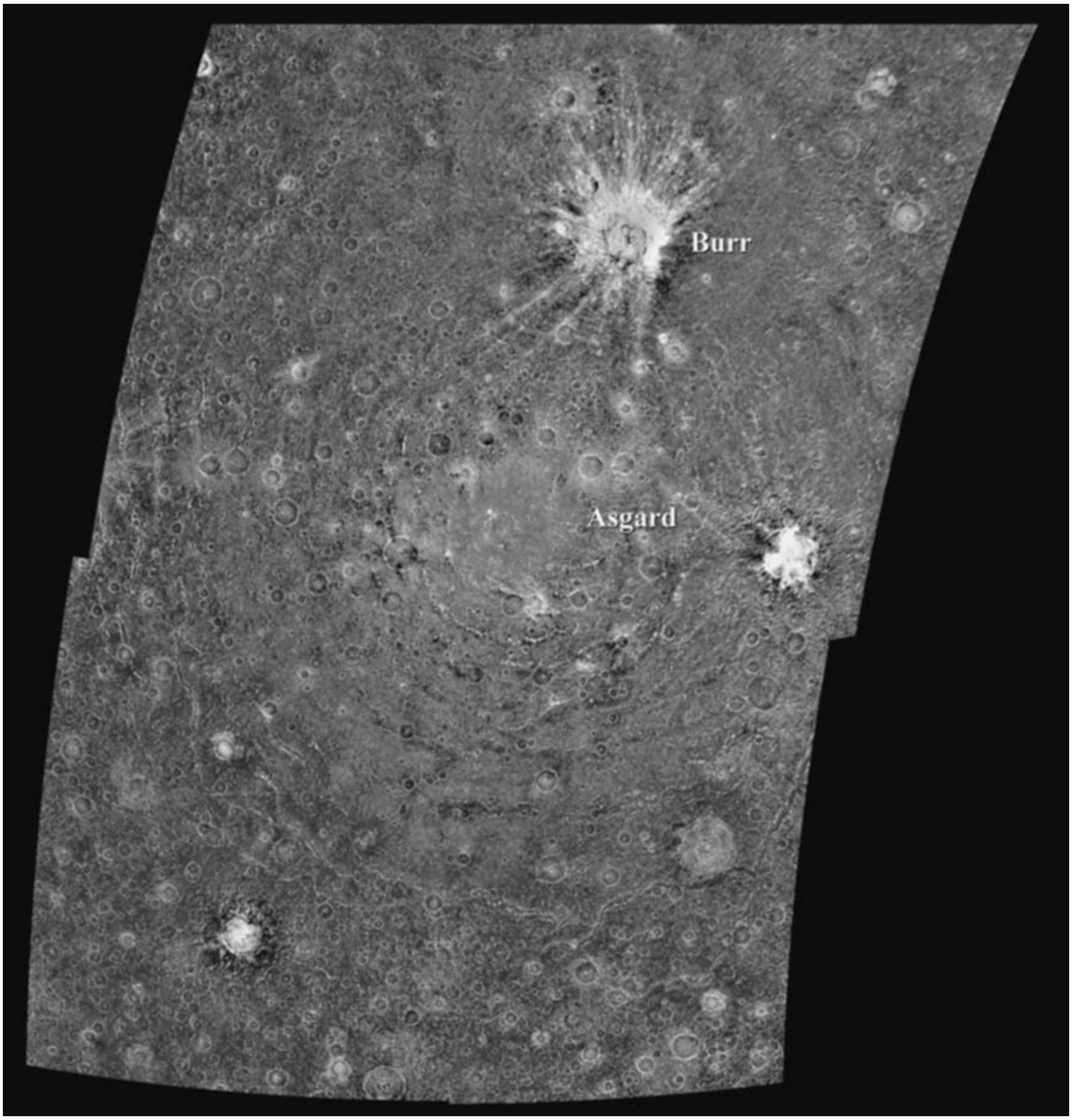

Figure 15.21. The Asgard impact structure of Callisto is located approximately at 30 °N and 142 °W. The structure which has a diameter of about 1700 km consists of a bright central zone surrounded by discontinuous rings. The original impact basin has been filled in by creep of the ice and the rings were formed by the transmission of the impact energy through the ice. The bright-rayed crater Burr north of the center of Asgard was formed during a relatively recent impact and confirms that the ice of Callisto is virtually clean and white. (Image PIA 00517, Galileo project, courtesy NASA/JPL-Caltech/DLR, Germany)

the ice crust that are spaced about 50 km part and have radii up to about 1500 km. A second, but smaller, multi-ring basin is called Asgard.

The surface of Callisto is covered by a layer of sediment composed of debris of various kinds of impactors and of residual dust released by sublimation of ice exposed at the surface. This sediment may be similar in origin to the sediment that covers the areas of old ice on Ganymede but differs from the reddish brown sediment on Europa, which contains salts derived from the ocean beneath the crust.

The landscape of Callisto shows evidence of differential sublimation of ice that results in the development of ridges and pinnacles and causes the shape of local ice plains to be concave up.

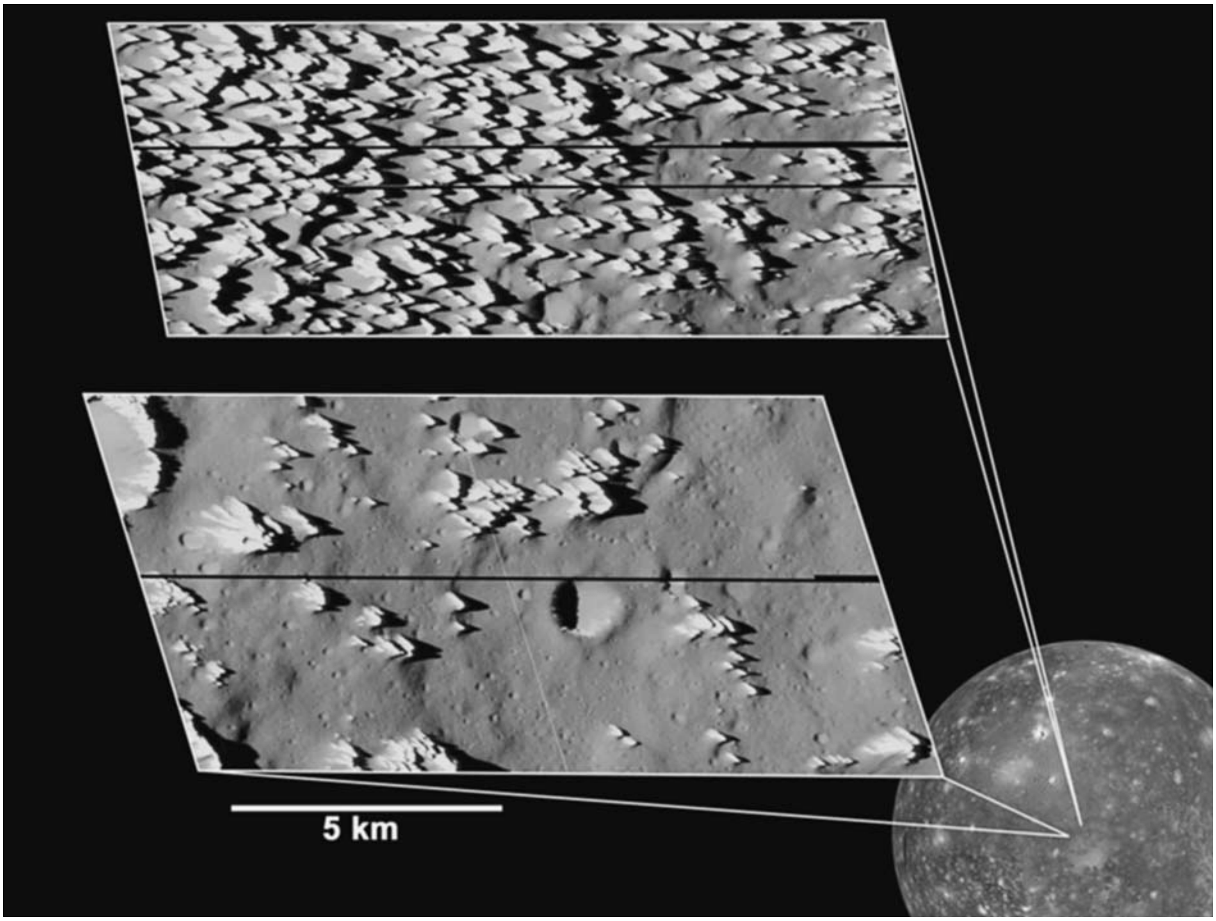

Figure 15.22. An area located south of the Asgard impact basin on Callisto contains clusters of pinnacles that appear to have formed by differential sublimation of ice. The pinnacles are between 80 to 100 m tall and may consist of ejecta from nearby impacts that occurred billions of year ago. The sublimation of ice continues until the layer of accumulated residue becomes too thick for the process to be effective. The pinnacles may eventually diminish in height, as suggested by the lower panel. The smallest object discernable in these images have diameters of about 3 m. These images have the highest resolution ever obtained from orbit of any satellite of Jupiter (Image PIA 03455, Galileo project, courtesy of NASA/JPL-Caltech/Arizona State University)

Sublimation of ice is effective in shaping the surface of Callisto because the surface is not being rejuvenated by cryovolcanic activity and because the surface temperature of Callisto is measurably warmer than the surface temperature of Europa and Ganymede.

15.6 Science Briefs

15.6.1 Period of Revolution of Io

The relation between the period of revolution (p) of Io and the length of the semimajor axis (a) of its orbit is expressed by Newton's version of Kepler's third law:

$$p^2 = \left[\frac{4\pi^2}{G(m_1 + m_2)}\right] a^3 \qquad (15.1)$$

where
m_1 = mass of Jupiter $= 1.90 \times 10^{27}$ kg
m_2 = mass of Io $= 8.89 \times 10^{22}$ kg
a = length of the semi-major axis $= 422 \times 10^6$ m
p = period of revolution of Io in seconds for a circular orbit.
$G = x$ gravitational constant $= 6.67 \times 10^{-11}$ newton m^2/kg^2.

Substituting into equation 15.1:

$$p^2 = \left[\frac{4 \times (3.14)^2}{6.67 \times 10^{-11}(1.90 \times 10^{27} + 8.89 \times 10^{22})}\right] \times (422 \times 10^6)^3$$

Note that the mass of $Io(m_2)$ is negligibly small compared to the mass of Jupiter and therefore can be omitted:

$$p^2 = \left[\frac{39.438}{6.67 \times 10^{-11} \times 1.90 \times 10^{27}}\right] \times 7.5151 \times 10^{25}$$

$$p = 1.529 \times 10^5\,s = 42.479\,h = 1.769\,d$$

This result agrees exactly with the period of revolution of Io in Table 15.1. Therefore, Io appears to be in a stable orbit because its period of revolution (p), and hence its average orbital velocity (v), have the exact values required by Newton's form of Kepler's third law.

The average orbital velocity of Io is: $v = d/p$, where (d) is the circumference of the orbit: $d = 2a\pi$ and p = period of revolution $= 1.529 \times 10^5$ s Therefore,

$$v = \frac{2a\pi}{p} = \frac{2 \times 422 \times 10^3 \times 3.14}{1.529 \times 10^5} = 17.33\,km/s$$

15.6.2 Ice-Dust Mixture of Callisto

The bulk density of Callisto (Table 15.1) is $1.790\,g/cm^3$, which means that it cannot be composed entirely of water ice (density $\simeq 1.00\,g/cm^3$) but also contains particles of refractory silicates and oxides (density $\simeq 3.00\,g/cm^3$). These data are used to estimate the volume fractions of ice and refractory particles that make up the body of Callisto.

The equation for this calculation was derived in Science Brief 10.6.1 from the requirement that the total mass of Callisto (M_c) is equal to the mass of ice (M_i) and the mass of the refractory particles (M_r):

The result expressed by equation 10.9:

$$\left(\frac{V_i}{V_c}\right) = \frac{D_c - D_r}{D_i - D_r} \qquad (15.2)$$

where

V_i = volume of the ice
V_c = volume of Callisto
D_c = density of Callisto
D_r = density of the silicate and oxide rocks
D_i = density of ice

Substituting values for the densities yields:

$$\frac{V_i}{V_c} = \frac{1.790 - 3.00}{1.00 - 3.00} = \frac{-1.21}{-2.00} = 0.60$$

Conclusion: About 60% of the volume of Callisto consists of water ice. Consequently, the refractory particles make up about 40% of its volume.

15.6.3 Valhalla and Asgard

Valhalla, the largest multi-ring basin on Callisto is named after a hall for slain warriors where, in Norse mythology, they live in comfort under the protection of Odin, one of the principal gods, until Doomsday when they will be called upon to help Odin to fight the Giants.

Valhalla is located in Asgard where the gods of Norse mythology dwell in their own palaces. For example, Valhalla is the home of Odin. Thor lives in Thrudheim, and Balder resides in Breidablik.

15.7 Problems

1. Calculate the average distance of Europa from Jupiter using Newton's version of Kepler's third law (See Science Brief 15.6.1 and data in Appendix Appendix 1, Table 15.1, and other sources in this book). (Answer: $a = 671 \times 10^3$ km).
2. Use orbital parameters of Ganymede to calculate the mass of Jupiter. Use data sources available in this book. (Answer: 1.90×10^{27} kg).
3. Calculate the escape speed of Ganymede (See Appendix Appendix 1 and Table 15.1). (Answer: 2.73 km/s).
4. Calculate the average speed of N_2 the surface of Ganymede (molecular weight = 28.013 atomic mass units, Avogadro's Number = 6.022×10^{23} molecules/mole, surface temperature $T = 107$ K). (Answer: $v_m = 0.308$ km/s).
5. Determine whether Ganymede can retain N_2 molecules in the space around it by using the

criterion that N_2 molecules can escape from Ganymede only if their speed multiplied by six is equal to or greater than the escape speed of Ganymede. (Answer: Ganymede can retain N_2 molecules).

6. Suggest one or several plausible explanations why Ganymede does *not* have an atmosphere even though Titan (Chapter 17) does.

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