SECTION 9: SATELLITES OF THE OUTER PLANETS

Many of the satellites of the outer planets have a significant component of ice in their make-up. To understand how that ice is distributed throughout the satellite, and to see if the body is fully differentiated, we need to have an understanding of the heating processes that the satellite could go through.

9.1 Heating processes

Assume the satellite formed by the accretion of lumps of ice and rock. Most of the outer satellites have densities that suggest they have cosmic abundances of water ice and rock, i.e. 60% and 40% respectively (there are notable exceptions to this). When volatiles condense in a near-vacuum, they do so at temperatures very much below their normal melting point, and go directly from vapour to solid. This means that a homogeneously accreted body undergoing no heating will not differentiate since the rock would not be able to separate out from the solid ice. There are various forms of heating that could occur during evolution, and we discuss three of them here.

FIGURE 9.1 (cross-section of an undifferentiated body)

9.1.1 Accretional heating

Accretional heating would occur as the result of the impact of accreting bodies. It is the most obvious way that satellites would have been heated. It is not certain how much of the kinetic energy released by the impact would have been retained by the satellite, but models generally suggest somewhere in the region of 10-50% of the energy is retained to heat the satellite.

FIGURE 9.2 (cross-section of a differentiated body)

The two largest moon's of Jupiter, Ganymede and Callisto, are so large that they would probably have been heated sufficiently by this method for melting to have occurred by the time they reached a radius of 1000-2000km. This would have enabled the rock to separate out from the ice and differentiation to occur. The rock would have sunk to the centre of the satellite surrounded by a layer of water ice. The separation itself would have caused more heating aiding the process. It is likely that a layer of ice/rock would still remain as a "crust", cooled as the heat from the surface radiated into space.

9.1.2 Radiogenic heating

Accretional heating would have been effective on only a few of the largest satellites. Another heating mechanism would be necessary for melting to occur on the smaller bodies. Some meteorites were heated soon after formation, by the decay of ^{26}Al, a short-lived isotope with a half-life of only 7×10^5 years. Because of its short half-life, practically no ^{26}Al exists today, but the daughter elements of the decay do and so we can infer that ^{26}Al was indeed present in some quantity during the formation of the solar system. There is some debate however, as to how much ^{26}Al was around at the time the satellites formed and hence how much this isotope contributed to the radiogenic heating of the outer satellites.

There are many other elements with half-lives much longer than ^{26}Al - ^{235}U, ^{238}U, ^{232}Th and ^{40}K. Radiogenic heating would have been much greater from these sources when the solar system was young. When trying to work out how much an effect this form of heating would have had, models generally assume that concentrations of radionuclides was similar to that on the Earth, Moon and meteorites. A body less than 600km in radius would not have become warm enough for internal melting and hence differentiation to occur. If we had a larger body, it may have been possible for the ice to melt in the interior, but the decline in radiogenic heat over time would have caused the ice to freeze once again.

Example: Consider a body of 700km radius. We start with a homogenous mix of ice/rock in the ratio 60:40. The body is too small for accretional heating to melt the body and the temperature at formation is therefore the same throughout. The satellite is big enough for radiogenic heat to act, but the heat within the satellite is unable to escape as fast as it is generated and so the interior warms up. After about 600 million years it begins to melt, reaching a maximum temperature at ~2 billion years. By this time, the interior of the satellite has differentiated, with the denser rock sinking to the centre forming a core of 140km radius, with the water forming a liquid layer just above it with a thickness of around 180km. Convection keeps the temperature at a constant value throughout this layer. Above the water layer, melting has not occurred, and retains its initial composition. From this point on, cooling of the body occurs as a result of the declining radiogenic heat production which is now less than that being radiated to space. As the cooling proceeds, the liquid water layer freezes, and becomes a layer of ice instead. If the satellite was larger, then the melting (and differentiation) would have reached closer to the surface. If any liquid water existed today, it would be beneath a very thick layer of ice.

FIGURE 9.3 (Fig 2.3, Rothery)

9.1.3 Tidal heating

The third sources of heating is due to the orbit of the satellite. As the satellite orbits its parent planet, it is continually flexing. Eventually the rotation of the satellite may become synchronous with its orbital period (like the Moon). If the orbit is completely circular, the speed of the satellite will remain constant, the tidal bulge will always point in the same direction and no tidal heat will be generated. However, if the synchronously orbiting satellite has even a slight ellipticity, its orbital speed will vary, being faster at its closest approach and slowest at its farthest approach (Kepler's laws of planetary motion). Because of this variation in speed, the synchronicity is not exact and a wobble results, called libration. The tidal bulge will therefore try to move in step with this wobble, and heat will be generated.

Left to its own devices, the satellite will eventually circularise its orbit, and tidal heat will no longer be generated. However, in practice, there are other gravitational influences, particularly from other satellites, which prevent this from happening. In some cases, this effect can be significant. Europa, Ganymede and Io are all affected by their periodical alignment and continue to generate heat by tidal forces. How much heat is generated depends on the thickness and other properties of the layers within the satellite. The most dramatic case of tidal heating is from Io, where 40-100 times as much heat is produced by tidal dissipation than by radiogenic heating. This has made Io one of the most active bodies in the solar system, as we shall see.

9.1.4 Factors relating to heating and differentiation

Obviously, not all satellites would have undergone all three heating processes. This does make it very hard to decipher the evolution of the outer satellites. An important factor to consider is that the melting and subsequent differentiation of a satellite may only have affected the interior, leaving a primordial mix of ice and rock as an outer crustal layer. The rapid cooling by radiation to space from the surface may have made it possible for even the largest of the moons to have kept an unmelted outer layer, despite being completely melted inside.

Making oversimplified generalisations is always dangerous, particularly is you fail to look out for the possible effects of those generalisations. Consider the partially differentiated body we dealt with previously. It was at one point (t_1) layered with a rocky core, liquid water, then an outer layer of rock and ice. The rocky ice layer is denser than the liquid water and so the body at t_1 would be gravitationally unstable. If the liquid water layer reaches close enough to the surface, the instability would cause the outer layer to crack and fracture providing a conduit for the liquid water to reach the surface. Taking this to the extreme, there could be a layer reversal, resulting in a pure ice outer layer and a mixture of rock and ice in the middle.

Another uncertainty in these models is the behaviour of the ice itself at the high pressures and low temperatures present inside these satellites. In the example we saw before, we assumed that heat loss would be by conduction through the ice and ice/rock mixture. However, if the solid ice is able to flow at a rate similar to the Earth's mantle due to convection, then heat could be transferred out on a similar scale to the conductive method. If this actually happened, the solid-state convection could prevent internal melting from occurring.

FIGURE 9.4 - (Stable phases of ice - Fig 2.4, Rothery)

The crystalline structure of ice is dependant upon temperature and pressure. The ice we are all familiar with is known as ice I. By compressing it and keeping it cold, the structure of the ice would change to form a different stable phase. There are several stable phases of ice, each with its own pressure-temperature boundaries. As an example, ice I at a temperature of 200K will transform to ice II as the pressure is increased. The liquidus shows the points at which the ices will melt; note that neither ice II nor ice VIII can melt directly. They must first change to another form of ice before they become a liquid. By estimating the pressure and temperature inside a satellite, we can determine what phase the ice will be in. However, the depth-pressure relationship will be different for each satellite as it is dependant upon factors such as the satellite's mass, density and degree of differentiation at a given point.

FIGURE 9.5 (Fig 2.5, Rothery)

In general though, a body smaller than 600km radius will have pressures low enough for ice I to be stable throughout. A little larger (700-800km radius, i.e. Rhea or Iapetus) the pressure near the centre may be large enough to permit ice II to be stable and in a large body like Callisto may have pressures to allow ices I, II, VI, and VIII to be stable at various points. The phases of ice may affect the evolution of an icy moon in a couple of ways. Solid-state convection generally does not occur between phase boundaries - this would inhibit the heat loss by convective means. Secondly, as the moon cools, a phase change could occur with no change in the pressure, i.e. from VIII to VI. This phase change would be associated with a decrease in volume, and would probably cause compressional tectonism to be evident on the surface.

One other complication in modelling is the contamination of the ice by other volatiles such as methane and ammonia. These would mix with the ice and lower the melting point of it. This may result in partial melting of the solid, with the potential for differentiation to occur in those parts. In addition, the properties of these contaminants, including their abundances and ability to convect are not well understood, leading to further uncertainty in the evolutionary models of the outer satellites.

9.2 Surface morphology of selected satellites

The four major satellites of Jupiter are Io, Europa, Ganymede and Callisto. All but Europa are larger than Earth's Moon, all are larger than the planet Pluto and Ganymede & Callisto are larger even than Mercury. Each has its own characteristics, but it appears that only Io is not dominated by water ice.

Table 9.1 Characteristics of some outer satellites

	Name	Radius (km)	Mass ($\times 10^{23}$g)	Density (gcm^{-3})
	Io	1820	891	3.52
	Europa	1500	487	3.45
Jupiter	Ganymede	2635	1490	1.95
	Callisto	2500	1065	1.62
	Rhea	765	24.9	1.33
Saturn	Titan	2560	1346	1.88
	Iapetus	747	18.8	1.16

9.2.1 Io

Io is the innermost of the Galilean satellites, and possibly the most exciting. It has a yellowish-orange colour and spectral studies have shown that it is covered by sulphur compounds and that water is rare. It has a very high albedo, higher than all other Galilean satellites.

Although its density is similar to rocky bodies, there does not appear to be evidence for silicate rocks exposed on the surface. It is a unique body in the solar system as it shows no evidence of impact craters on its surface. Craters of a few km diameter should form every 10,000 years or so on Io, which suggests that the surface of Io is very young indeed. It has very little atmosphere and so weathering cannot be used to explain the absence of craters. Early reports of impact features on Io turned out to be volcanic landforms, still active, as photographed by Voyager. Io remains the most active body in the solar system along with Earth. Images from Voyager reveal calderas, flows emanating from vents and bright frost deposits of SO_2. This active volcanism is clearly the reason for the young surface. Any record of early impact cratering events would have been wiped out many thousands, possibly millions of years ago.

The topography of Io is generally quite smooth in appearance, but occasional mountains pop up, giving a maximum relief of 9km. These mountains suggest that there is a strong stable layer within Io capable of supporting such structures. The most likely candidate for this is solid silicate rock and there will probably be some source of silicate magma as well as that of molten sulphur.

35% of Io's surface was photographed at an average resolution of 5km by Voyager (best was 0.5km). Three main geological units were recognised - mountain, plains and vents. The mountains seem to be the oldest features on Io having been modified by both erosional and tectonic activity.

Plains are the predominant landform on Io and make up ~40% of the mapped area. There are three types of plain which have been distinguished:

1. Intervent plains: smooth surfaces, constant albedo. Probably represents fallout from volcanic plumes.
2. Layered plains: ~9% of the mapped area. These have smooth flat surfaces bounded by escarpments transected by faults.
3. Eroded layered plains. Make up less than 1% of the mapped area and are restricted to the south polar region. They provide evidence for erosional processes having taken place.

More than 300 vent-related structures have been mapped on Io. The largest are generally found in the equatorial regions. Ionian flows cover large areas, with some flows reaching more than 700km in length and take on many forms. Io has many hot-spots with temperatures up to 600K, consistent with sulphur volcanism, but not completely inconsistent with quiescent silicate lava pools either.

9.2.2 Europa

Europa, the next world out from Jupiter, has a vast number of narrow, sinuous cracks of all sizes, from the radius of the planet to the limit of resolution. It is the smallest of the Galilean satellites with a density similar to that of our own Moon. It is however, completely un-Moon-like with few craters indicating a young surface, with a spectrum dominated by ice. But, by density considerations, the majority of the interior of Europa must be made of silicates.

Europa has two distinct terrain types - a bright plains unit and a darker mottled terrain. Both terrains are cut by dark bands sometimes with a bright strip through them, and occasionally the band itself is exclusively bright. Both terrains and bands are superimposed by ridges up to 200m high. These appear to be the youngest form of tectonism on Europa. The mottled terrain appears to be superimposed on the plains unit, so the plains are probably the oldest unit on Europa. By counting craters it would seem that the surface of Europa is no greater than 10 to 100 million years old. The mottled terrain has various small brown patches which could represent areas of ice mixed up with silicate minerals. Europa is dominated by extensional tectonism. This implies that some kind of global expansion has taken place, although how is still a matter of debate. By consideration of radiogenic and tidal heating, and other factors we expect the lower part of the water layer to be liquid.

9.2.3 Ganymede

The largest of the Galilean satellites, it too can be split into distinct regions. Ganymede's surface is divided into dark and bright terrains. The dark appears in polygonal patterns and are heavily cratered. The brighter terrain appears as bands separating the dark terrains are less heavily cratered. The bright terrain is clearly younger than the dark with strong grooves also being present, indicative of widespread tectonism and volcanism having occurred. Both units have many young fresh craters which show that Ganymede has been inactive for some time. As with Europa, Ganymede may have undergone some global expansion in the past, creating the bright terrain, many of which show extensive grooving. Much of the bright material may have been extruded as water or an icy mush through faults and fractures. The only major event that appeared on Ganymede after the formation of the bright terrain was an impact event, creating a large 275km diameter multi-ringed basin.

9.2.4 Callisto

Callisto is the second largest of the Galilean satellites and also the least dense. Callisto is intensely cratered all over, indicating that it is pretty much a dead world. The surface is dark and has a low albedo which is consistent with any icy surface being vaporised by the countless impacts over time. The ejecta of younger craters have a much higher albedo which indicates that some kind of impure ice-rich material lay below the surface of these craters.

Callisto has several multi-ringed basins, the largest of which (Valhalla) has an outermost ring of 4000km in diameter. Subtle differences in the form of the basins give clues as to the strength and thickness of the lithosphere of Callisto at the time of formation. In the two largest basins there is a bright area at the centre of the feature that looks as though it was once a raised structure (like a central peak) which collapsed, either because it was made of a very weak material (icy slush) or the lithosphere was too thin to support it. In Valhalla's case, the rings are ~15km wide and are spaced only 20-30km apart. No ring completes a circle around Valhalla - instead the ring-like structures are made of arcs between 200 and 500km in length. These arcs have an unusual characteristic in that they have scarps facing inwards closer to the basin, and outwards facing further from the basin. Put simply, the thinner the lithosphere, the more rings are expected and the closer their spacing. From this alone, we can conclude that the lithosphere of Callisto was much thinner at Valhalla than on the Moon. It is believed that the lithosphere of Callisto is much thicker now than it was then.

9.2.5 Titan

Titan is the largest satellite of Saturn and is the focus of great interest amongst scientists. It is the only solid body beyond Mars with a substantial atmosphere. The atmosphere is 200km thick and consists mainly of nitrogen, methane, plus traces of hydrogen and organic compounds. It is completely opaque, which means that no images of its surface have ever been taken - we await the results of the Cassini mission to tell us what the surface is really like. Titan is big enough for both accretional heating and radiogenic heating to have melted its interior. We therefore expect that Titan is at least partially differentiated, although to what degree we don't know. Again, perhaps Cassini will be able to tell us that.

Reference List

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