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Europa

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Europa!!!

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(http://homepage.mac.com/joebergeron/europa.html)

Abstract

This paper tells the story of the moon of Jupiter named Europa. Discussed are Europa's discovery, basic parameters, orbit, tides, surface features, interior, magnetic field, atmosphere, and possible future data-gathering missions to Europa. This paper shows that Europa's surface features, induced magnetic field, and observed thin oxygen atmosphere indicate the presence of a liquid salty ocean beneath Europa's icy surface layer.

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1. Introduction

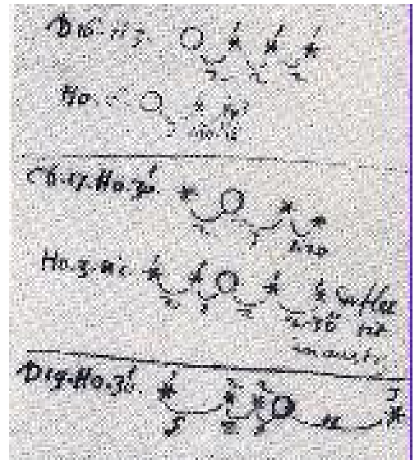

Figure 1.1: Part of a page of Galileo's observational notes on the movement of Jupiter's four largest moons. The circle is Jupiter and the stars are the four moons numbered according to their proximity to Jupiter. This image shows the orbital motion of the moons.

Imagine yourself back in 1610, gazing up into the heavens at the sparkling blanket of stars, wondering what in the universe they are like as you squint through your telescope… Doing just that, Galileo Galilei discovered Jupiter's four largest moons, now called the Galilean satellites in his honor. Figure 1.1 shows a copy of part of Galileo's observations of the satellites.[1]

Figure 1.2: Image of Europa riding off on Jupiter, the white bull.

Meanwhile a competing astronomer named Simon Marius also discovered the same moons, but he named them individually after Greek mythological figures. Thus Europa is named after the beautiful Phoenician Princess who was seduced by Zeus[2] in the form of a beautiful white bull (see Figure 1.2)[3].

Galileo's and Marius's discovery of the Galilean Satellites was the first discovery of planetary satellites that obviously did not belong to Earth.[4] Europa is special because of its chaotic surface features that look like our frozen oceans. These features and other observations to be discussed later indicate there may be liquid water

[1] Morrison, D. (1940). Exploring Planetary Worlds. New York, Scientific American Library.
[2] Zeus = Jupiter, same god but different names for Roman & Greek languages
[3] http://homeppage.mac.com/cparada/GML/Europa.html
[4] Morrison, 153

under Europa's icy outer layer. The goal of this paper is to bring these unique features to life by going over what is known about Europa and how some of this information was determined. More specifically, it will touch on what might create Europa's surface features, how Jupiter's and Europa's magnetic fields interact and what this interaction implies, as well as what might be done to learn more and verify what we have already determined. The discussions in this paper will show that Europa's orbit, resulting tides, and magnetic field create Europa's surface features and indicate the possible existence of a salty ocean under the icy surface layer.

1.1 Spacecraft Missions to Europa

In the early 1970's the United States sent the Pioneer 10 and 11 spacecraft to Jupiter. The images of the Galilean moons they obtained were fuzzy and dim. The Pioneer missions were mainly to see if such a flight though space past Jupiter's large magnetic field was possible for data gathering instruments.

The next trips were the 1979 Voyager I and II missions to Jupiter and the Galilean moons and beyond. Most of the excitement over Europa and her sister moons started because of the implications of the clearer images and data obtained by the Voyager missions. These images showed some fascinating characteristics that indicated that Europa was one of the smoothest objects in our solar system and could be covered with ice. Scientists began thinking there might even be water under the ice.

The latest Jupiter program was the recent Galileo mission that revealed more about Jupiter and the four Galilean moons. More specifically scientists wanted to learn about Jupiter's atmosphere and the effects of Jupiter's large magnetic field, to examine more closely Io's active geology and Europa's surface, and to gather more data on Ganymede and Callisto. The mission to Jupiter was so successful that NASA had Galileo orbit an extra two years and then another four more years after that when NASA crashed the spacecraft into Jupiter in the Fall of 2003.

In order to gather the desired data, the Galileo orbiter was outfitted with many instruments. Operating commands were preprogrammed into the orbiter's computer system because it took more than an hour for radio signals to go between the orbiter and Earth. The spacecraft weighed 2,223 kilograms on Earth with a maximum length of 5.3 meters (17 feet). Twelve 10-newton (2.25 pound-force) thrusters and a single 400-newton (90 pound-force) engine fueled by monomethylhydrazine fuel and nitrogen-tetroxide oxidizer propelled this spacecraft. The spacecraft spinning around a major axis, rotating at about 3 rpm, while the bottom part counter-rotated to maintain a fixed orientation in space, stabilized its flight. Counter-rotation, in order to provide a fixed orientation for the spacecraft, stabilized the bottom part. This division provided the stability and steadiness that some of the instruments required.

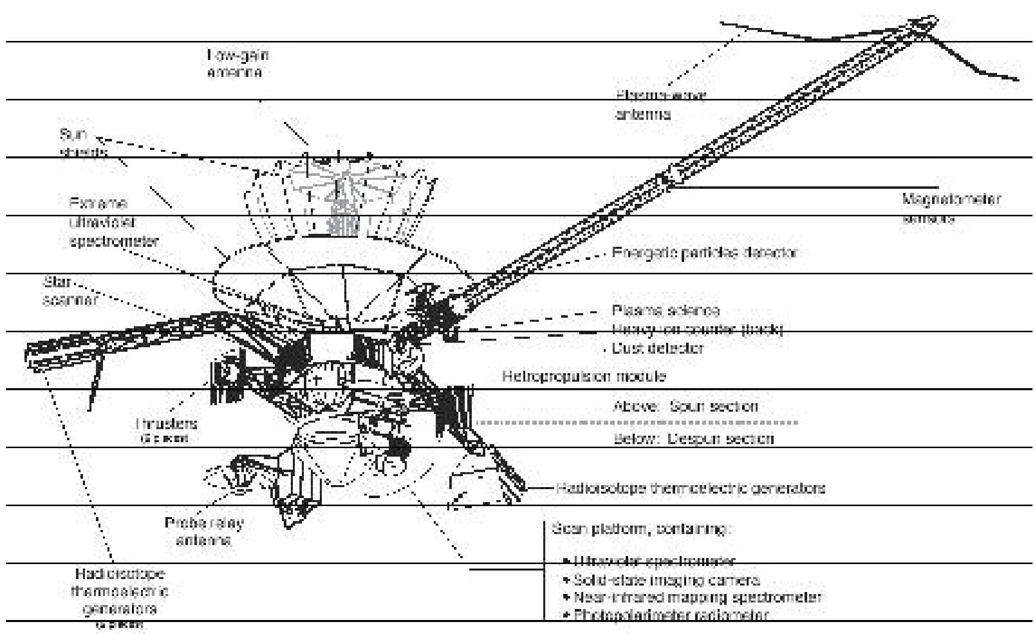

Figure1.1.1: The Galileo Spacecraft[5]

[5] NASA Galileo End of Mission Press Kit: http://galileo.jpl.nasa.gov/news/release/galileo-end.pdf

The basic instruments attached to each part and a brief description of what they were used for is shown in Appendix A. The images shown in this paper come mainly from two of Galileo's instruments: Solid State Imaging (SSI) and Near-Infrared Mapping Spectrometer (NIMS).

The SSI was designed to study atmospheric motion, geologic formations, composition of satellite surfaces, and the vertical structure of features in Jupiter's atmosphere. It consisted of a 1500 mm (59 inch) focal length, narrow-angle telescope (inherited from Voyager), an image sensor, a filter wheel, a focal plane shutter, and electronics. The camera it used had high-resolution, a large field of view, and used a charge-coupled device (CCD). The SSI used seven near-infrared spectral filters and one clear filter that allowed its images to capture different vertical structure, color, and morphology. It was the highest resolution instrument on the Galileo spacecraft and spanned a wavelength from visible to near-infrared.

Figure 1.1.2: Diagram of the SSI camera with the various parts labeled.[6]

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

[6] http://www2.jpl.nasa.gov/galileo/sepo/images/camera.jpeg

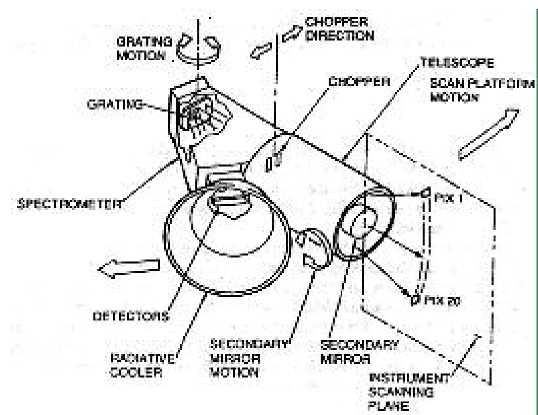

Figure 1.1.3: Diagram of the NIMS camera with the various parts labeled.[7]

The NIMS was designed to look at the surfaces of Jupiter's satellites to see what they are made of and to study the atmosphere of Jupiter in order to identify its various characteristics. It consisted of a reflecting telescope, a spectrometer that used a grating to disperse the light collected by the telescope, and it had detectors of indium antimonide and silicon. The NIMS looks at the near-infrared range from reflected to sunlight and thermal radiation spectral range 0.7-5.2 microns.

2. Basic Europa Statistics

Europa is the second closest of the four Galilean moons to Jupiter (Figure 2.1) and it has the second highest density of 2,990 kg/m^3. It is the smallest Galilean moon (Table 2.1) with a diameter of 3138 km and a mass of $479.7*10^{20}$ kg. Europa is even smaller than our moon; it is so small it can fit between the East and West coasts of the United States.

Figure 2.1: Jupiter and the Galilean Moons: Top (closest to Jupiter) to bottom: Io, Europa, Ganymede, Callisto[8]

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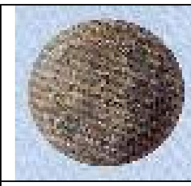
[7] http://www.jpl.nasa.gov/galileo/gem/fact.html

[8] NASA's JPL Photojournal on Europa: http://photojournal.jpl.nasa.gov/catalog/PIA00600

Table 2.1: Comparison of statistics for the Galilean Moons and Earth's Moon.

					
	Io	Europa	Ganymede	Callisto	Moon
Diameter	3630 km	3138 km	5262 km	4800 km	3476 km
Mass	$893.3 * 10^{20}$ kg	$479.7 * 10^{20}$ kg	$1482 * 10^{20}$ kg	$1076 * 10^{20}$ kg	$735 * 10^{20}$ kg
Density	3,530 kg/m^3	2,990 kg/m^3	1,940 kg/m^3	1,851 kg/m^3	3,340 kg/m^3
Orbital Distance	$421.6 * 10^3$ km	$670.9 * 10^3$ km	$1070 * 10^3$ km	$1883 * 10^3$ km	$384.4 * 10^3$ km
Orbital Period	1.77 days	3.55 days	7.15 days	16.69 days	27.3 days
Orbital Eccentricity	0.004	0.009	0.002	0.007	0.055

On the other hand Europa has a water volume of 2.9×10^9 km^3, about twice that of Earth's 1.37×10^9 km^3 water volume. This water appears as ice on Europa's surface because its temperature is –260°F (110.778K). Europa's ice has a visual albedo, a surface reflectance or brightness, of 0.64 where one is white and zero is black. Europa has an orbital speed of 13.74 km/sec and it has an orbital inclination (the angle of Europa's orbit compared to Jupiter's equator) of 0.470°. Its rotational period essentially equals its orbital period. Europa also has a surface gravity of 1.3 m/sec^2 and an escape velocity of 2.02 km/sec. All of these features work together, as this paper will show, to form surface features that are up to 900 meters tall.

3. Orbit and Tides

Initially it was thought that Europa had a circular orbit and was tidally locked into synchronous rotation such that one side of Europa constantly faced Jupiter. A key feature of such a circular orbit is the orbital velocity. We can approximate this value by equating Newton's Law of Gravity to his Second Law of Motion,

$$\frac{GM_J M_E}{r^2} = M_E a = \frac{M_E v^2}{r}, \tag{3.1}$$

where the centripetal acceleration is simply the orbital speed squared divided by the radial distance, G is the gravitational constant, M_J is Jupiter's mass, M_E is Europa's mass, r is the radial distance between the two, a is Europa's centripetal acceleration, and v is Europa's orbital speed:

$$v = \sqrt{\frac{GM_J}{r}}\,. \tag{3.2}$$

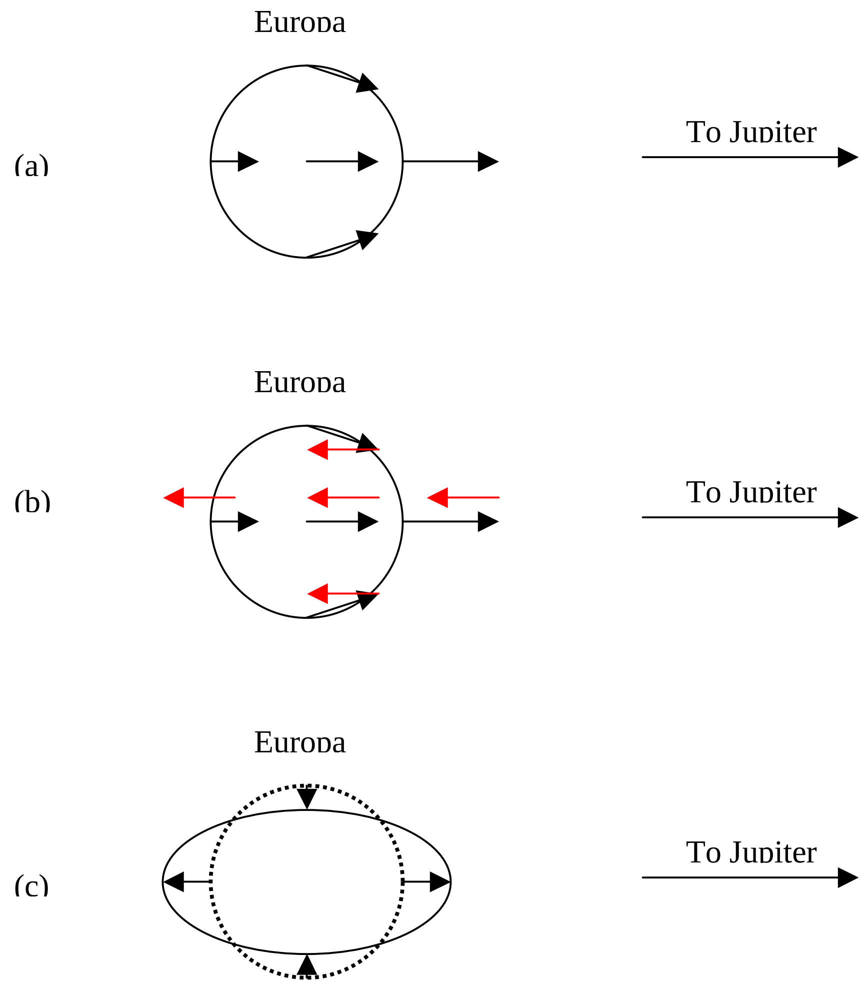
This equation shows that as the radius increases, the speed decreases and vice versa. Solving this equation and plugging in the appropriate values we obtain an orbital speed of 13.74 km/sec. We can arrive at Kepler's Third Law of Motion by setting Equation 3.2 equal to the standard circular velocity equation of distance $2\pi r$ divided by time, $p_{orbital}$, and reducing this new equation to get

$$\frac{4\pi^2}{GM_J} r^3 = p_{orbital}^2\,. \tag{3.3}$$

Kepler's Third Law of Motin shows that as the radial distance increases, the time it takes to orbit increases. Thus for a circular orbit the period of time it takes to orbit would be constant because the radius is constant.

As Europa orbits around Jupiter, Jupiter's gravitational force pulling on Europa is strongest on the surface closest to Jupiter and it pulls the top and bottom edges of Europa slightly in toward Jupiter's center, as seen in Figure 3.1 a.

Figure 3.1: (a) Vector components of Jupiter's gravitational pull on various points of Europa; (b) subtract the center vector value from the all the points; (c) the distortions in Europa's shape that this subtraction causes (tidal bulges).



As seen in Figure 3.1b and 3.1c, Europa is elongated by the pull of Jupiter such that Europa's radius, R_E, is no longer constant. Thus the tidal force is just the change in gravitational forces between a specific test point and the center. Subtracting the gravitational force at the center from the gravitational force vector at a specific gives the tidal force at that point:

$$F_{test} - F_{center} = F_{tidal} \,. \tag{3.4}$$

Equation 3.4 can be written out in terms of the general force of gravity equations for each component,

$$F_{front} - F_{center} = \frac{GM_J M_t}{(r - R_E)^2} - \frac{GM_J M_t}{r^2}, \tag{3.5}$$

and solved using a Taylor Series expansion on the front component. Since the radius of Europa is significantly less than the distance between Jupiter and Europa, the change in the forces can be approximated as the derivative of the general force of gravity equation:

$$\Delta F = F_{tidal} = \left|\frac{dF}{dr}\right|\Delta r = \left|\frac{dF}{dr}\right|R_E . \tag{3.6}$$

Both solving methods produce a tidal force of

$$F_{tidal} = \frac{2GM_J M_t}{r^3} R_E \tag{3.7}$$

for any given test mass, M_t, and radius of Europa, R_E. This equation shows that as the radius increases, the tidal force significantly decreases; as the radius decreases, the tidal force significantly increases.

One might wonder why this tidal force doesn't pull Europa apart. If Europa just depends on its own self-gravity to hold it together, then as long as its orbital radius is greater or equal to Roche's Limit, it will stay together. Roche's Limit is where the tidal force and the satellite's self-gravity at a specific location on the satellite are equal. To approximate Roche's Limit simply equate these two force equations and solve for the distance r between the planet and satellite:

$$F_{tidal} = F_{self-gravity} \tag{3.8}$$

$$\frac{2GM_J M_t R_E}{r^3} = \frac{GM_E M_t}{R_E^2} \tag{3.9}$$

$$r = \left(\frac{2M_J}{M_E}\right)^{1/3} R_E . \tag{3.10}$$

Multiplying this result by the constant $\dfrac{\frac{4}{3}\pi R_J^3}{\frac{4}{3}\pi R_J^3}$, where R_J is Jupiter's radius, and simplifying the equation, produces a Roche's Limit in terms of densities, ρ, of Jupiter and Europa and Jupiter's radius instead of mass and the satellite's radius:

$$r = \left(\frac{2\rho_J}{\rho_E}\right)^{1/3} R_J . \tag{3.11}$$

If ever a satellite goes inside this radial distance the tidal force will pull it apart and the pieces would form a ring around the planet.

However, observations have shown that Europa's orbit has a very slight eccentricity of 0.009 that is caused by the pulls of its neighbors Io and Ganymede. These three moons were found to be in a 2E:4I:1G orbital resonance, meaning that for every two orbits Europa makes, Io makes four and Ganymede makes one. This pattern is drawn out in Figure 3.2 to show the three moon's movements. Thus every 3.5 days, Europa gets a tug in a consistent direction by either Io alone or Io and Ganymede together.

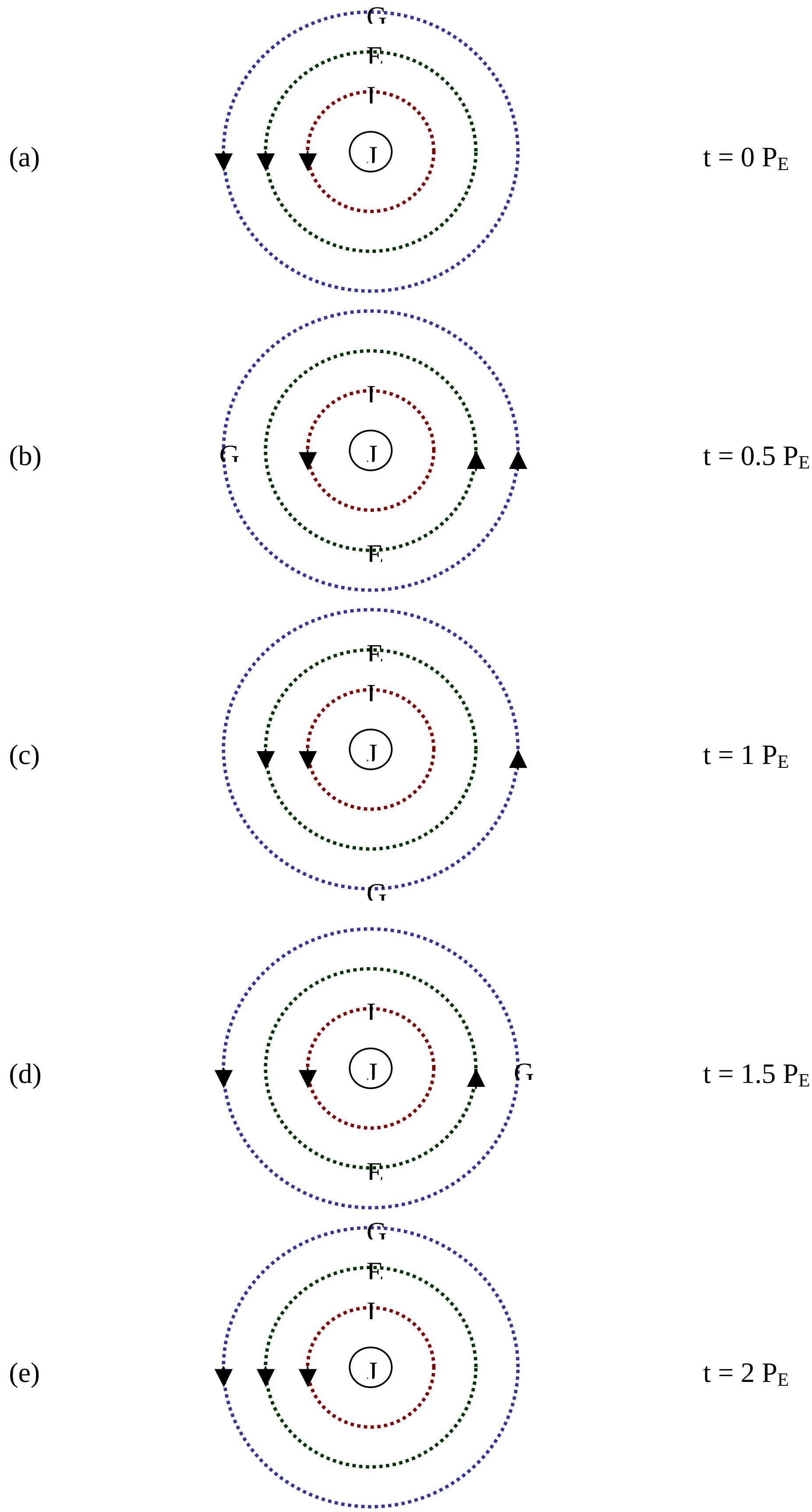


Figure 3.2: Europa's 2:4:1 Orbital Resonance: For every half (b) or one and a half (d) orbits of Europa, Ganymede goes a quarter of the way in its orbit and Io makes one full orbit. (c) For every full orbit of Europa (3.5 days), Io makes two and Ganymede is half way. After seven days the moons are realigned in the position they started (a & e).

The forces on Europa are strongest when these three moons are in line with each other every seven days. Of all the forces acting on Europa, Jupiter's is the strongest, then Io's, and finally Ganymede's is the weakest:

$$F_{J-E} = \frac{GM_J M_E}{r^2} = 1.35 * 10^{22} N \qquad (3.12)$$

$$F_{I-E} = \frac{GM_I M_E}{\left(r_E - r_I\right)^2} = 4.6 * 10^{18} N \qquad (3.13)$$

$$F_{G-E} = \frac{GM_G M_E}{\left(r_G - r_E\right)^2} = 3.0 * 10^{18} N . \qquad (3.14)$$

Io's force is greater than Ganymede's, even though Ganymede is significantly more massive, because Io is significantly closer to Europa than Ganymede. The effect of Io's and Ganymede's forces pulling on Europa is a slight tug but it is thought that it causes significant stress on Europa and results in its unique surface features. Thus the forces of Io and Ganymede give Europa's orbit a slight tug that causes the orbit to be slightly elliptical.

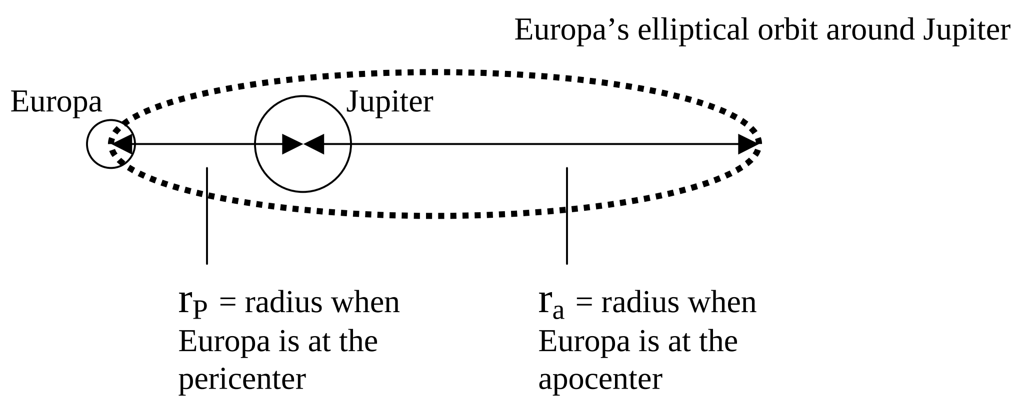


Figure 3.3: Europa's highly exaggerated elliptical orbit

In an elliptical orbit the satellite has two extreme points: the pericenter where it is closest to the planet and the apocenter where it is farthest from the planet. Observations show that a satellite in an elliptical orbit moves faster, v_p, when it is closest to the planet, r_p, and slower, v_a, when it is farther from the planet, r_a. The relationship between radial distance and orbital speed can be proved using the Law of Conservation of Angular Momentum, which states that the angular momentum at each of those two extreme points must be equal if there are no external torques on the system:

$$mv_a r_a = mv_p r_p \tag{3.15}$$

$$v_a \frac{r_a}{r_p} = v_p . \tag{3.16}$$

The ratio $\frac{r_a}{r_p}$ is greater than one, thus the orbital velocity at the apocenter is less than that at the pericenter. Thus the radial distance increases as the orbital velocity decreases and the radial distance decreases as the orbital velocity increases.

To see how these changes in radial distance and orbital velocity affect Europa, we must treat Europa's tidally distorted surface as a sine wave (where the curves above the x-axis represent the tidal bulges, and the curves below represent the sides pushed in) and look at the Fourier Components of this wave in Europa's changing orbit. The sum of these components is what we actually see happening on Europa's surface. There are three main Fourier Components[9] of the bulge to look at: primary, change due to distance variation, and change due to speed variation. The primary component is what Europa's surface would look like if it had a circular orbit tidally locked on Jupiter into synchronous rotation. In this case there is only one possible sine wave (Fig 3.4a) and the tidal bulges have a constant size and point directly to a fixed point of Jupiter during each of the four phases of Europa's orbit (Fig 3.4b).

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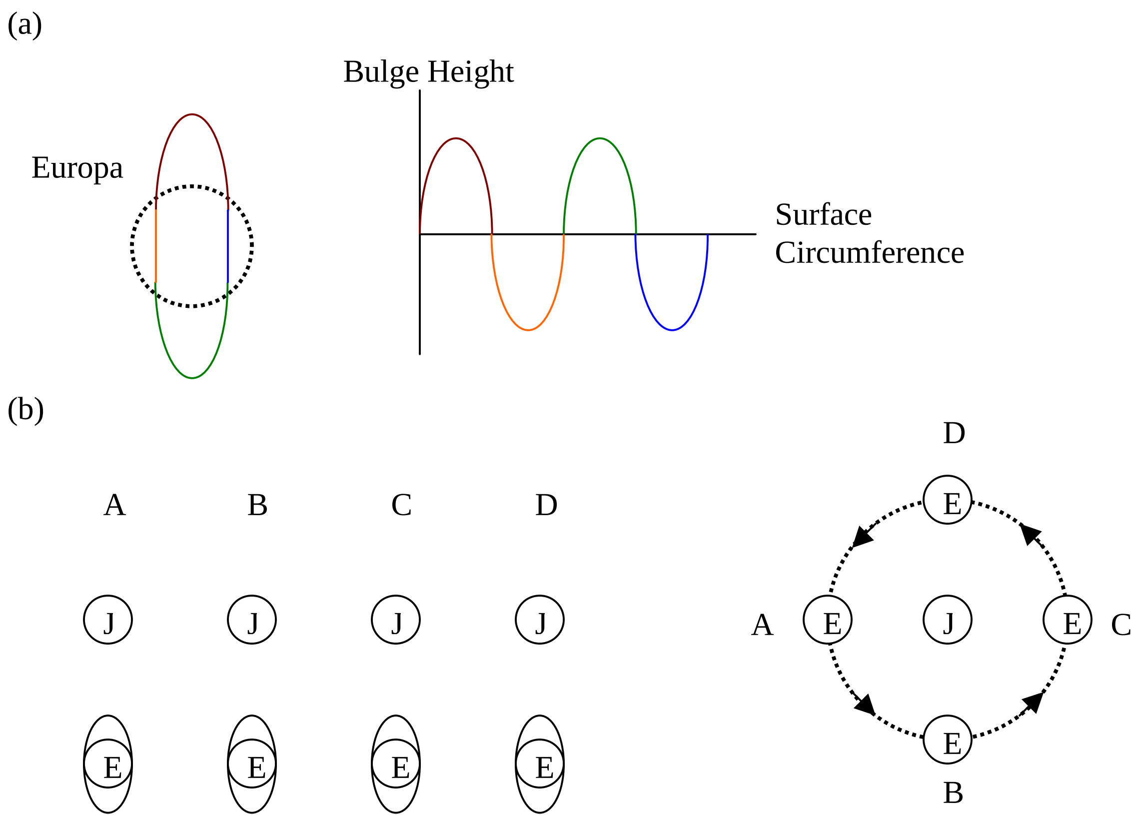
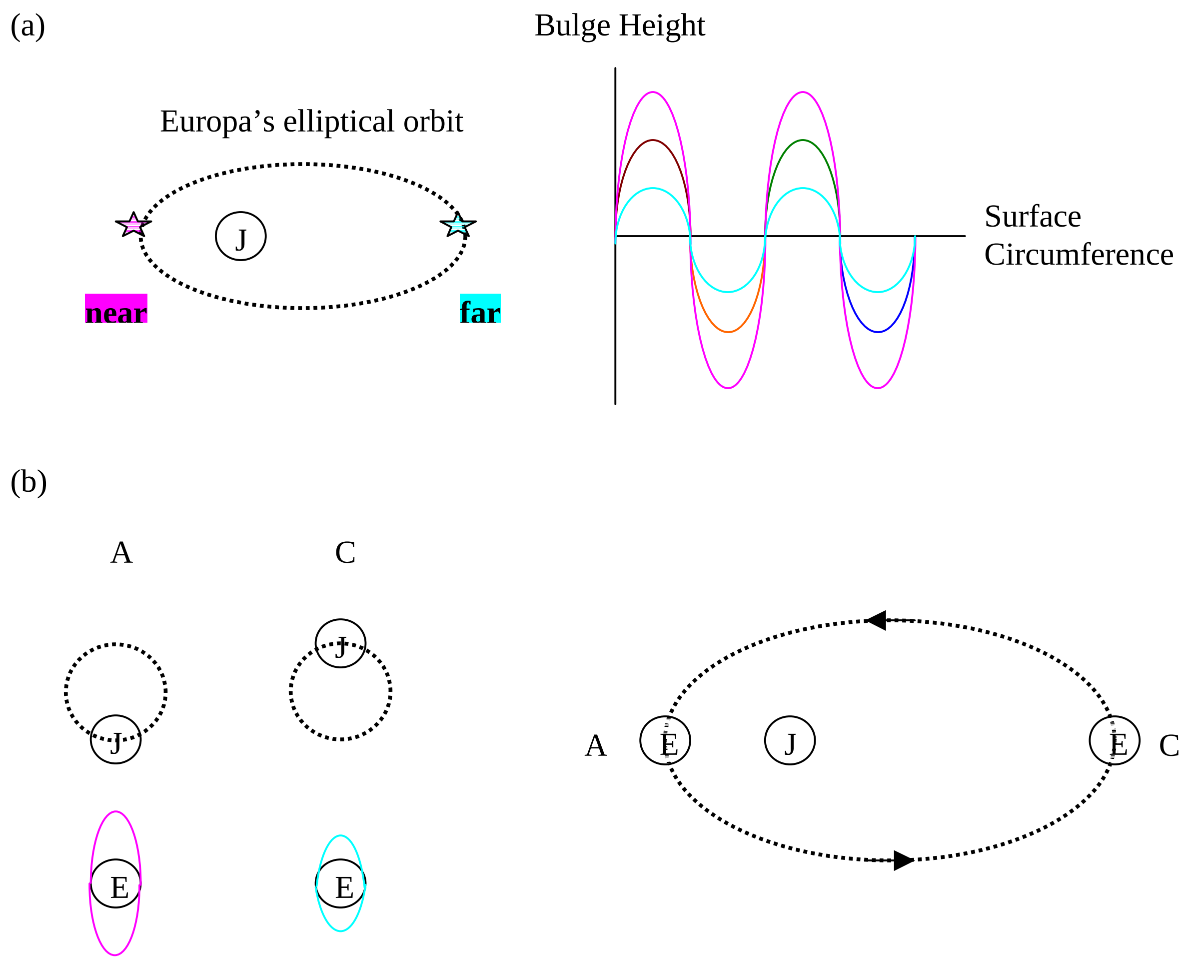
[9] Greenberg, R., P. Geissler, et al. (1998). "Tectonic Processes on Europa: Tidal Stresses, Mechanical Response, and Visible Features*1." Icarus **135**(1): 64-78.

Figure 3.4: Primary Component: (a) Europa's surface cut up and spread out as a sine wave. (b) The tidal bulges, as seen from Europa in a circular orbit, are a constant size and are synchronously locked on Jupiter throughout Europa's circular orbit.



On the other hand, if Europa has an elliptical orbit in which the orbital radius is changing from close to far, the tidal bulges are larger when Europa is closer to Jupiter and smaller when Europa is farther from Jupiter (Fig 3.5a). Thus there are two possible sine waves that represent Europa's surface: one with a larger amplitude when Europa is closest to Jupiter and the other with a smaller amplitude when Europa is farther from Jupiter (Fig 3.5b).

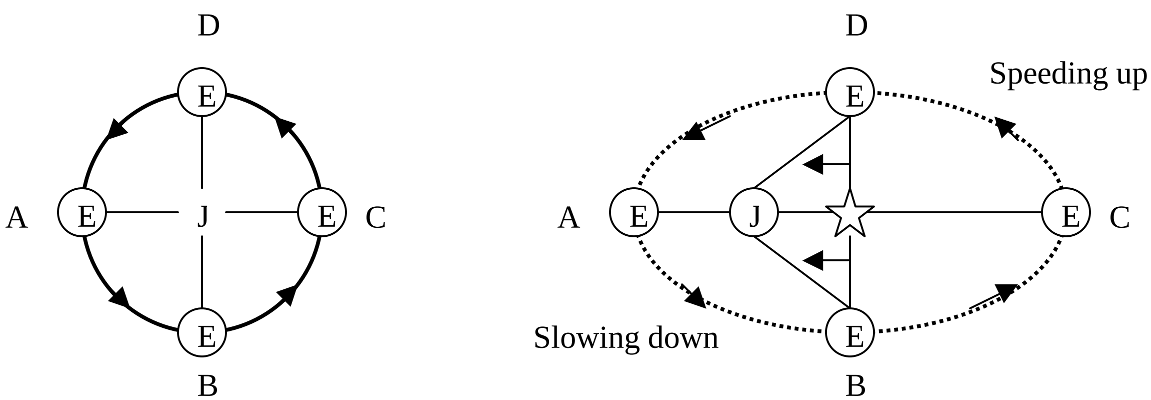
Figure 3.5: Change in Distance Component of an elliptical orbit: (a) Surface sine wave for Europa. (b) Tidal bulges on Europa are larger when Europa is closer to jupiter and smaller when Europa is farther from Jupiter. The spin of Europa's bulges cannot keep up with Europa's orbit around Jupiter so from Europa's perspective it looks like Jupiter is moving in a circle.



As discussed earlier, Europa's orbital velocity also changes for an elliptical orbit, but the spin rate remains constant. The velocity decreases as Europa moves away from Jupiter and increases as Europa moves closer to Jupiter. Europa's tidal bulges and rotation speed cannot respond instantaneously to these changes in orbital velocity so the bulges lag slightly behind. Thus from Europa's perspective, Jupiter appears to move in a circle (Figure 3.5b). Viewed from Europa, the time lag in the movement of Europa's tidal bulge makes it look like Jupiter is off to the left of

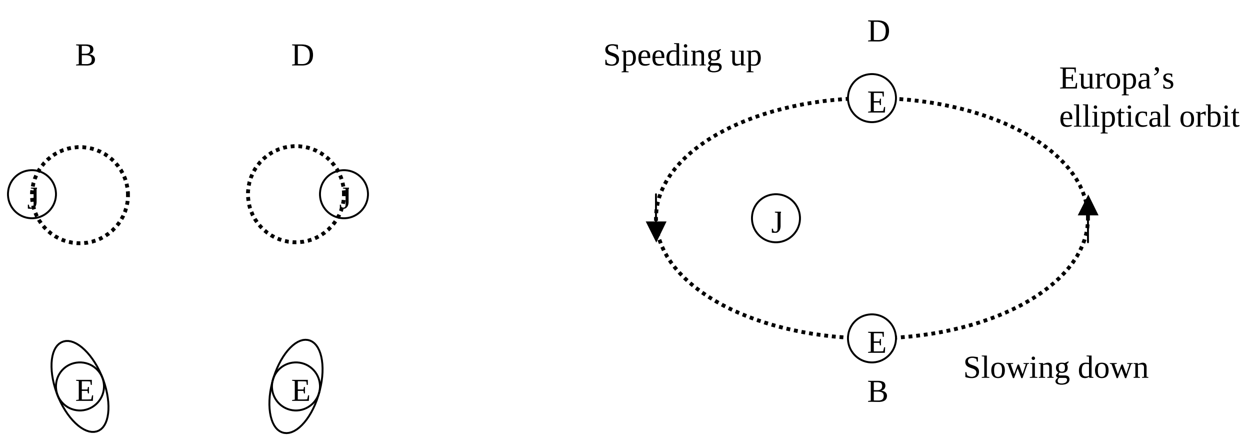
Europa when Europa's orbital velocity is slowing down, and like Jupiter is off to the right when Europa is speeding up (Figures 3.6 and 3.7).

Figure 3.6: The Change in Velocity Component due to Europa having a slightly elliptical orbit can be seen by comparing a circular and elliptical orbit to see where Jupiter is in relation to Europa during the times Europa speeds up and slows down.



Added together these three Fourier Components result in Europa having a slightly non-synchronous rotation about Jupiter and tidal bulges that change in size and in orientation with orbital speed as seen in Figure 3.7.

Figure 3.7: Total Tides for Europa's bulges when their velocity changes. The sizes of the bulges change consistently but when Europa is slowing down Jupiter appears to be off to the left and when Europa is speeding up Jupiter appears to be off to the right.



All of this stretching and compressing of Europa's surface due to its slightly non-synchronous and eccentric orbit causes changes in tidal bulges, heats Europa, and causes surface stress. The results of this heating and surface stress are small but significant as they add up over time to form the fascinating surface features that images of Europa's surface have made visible.

4. Surface Features

Europa's surface features are unique in that they are comprised of seemingly random bits of plains, mottled terrains, and chaotic terrain. Bands, lines, ridges, troughs, icebergs, and craters crisscross and spot these features. As discussed above, the heating of the surface and subsurface material along with surface stress cause most of these features. There are four main sources of surface stress on Europa:[10]

1. changes in rotation rate
2. changes in orbit, including changes in orbital distance and orbital eccentricity
3. changes in radius of Europa during its geophysical evolution
4. polar wander could cause stress fields to vary relative to the geographical features on Europa's surface.

The first three are basically the Fourier Components we talked about earlier. Surface stress generally results in tectonic resurfacing (repeatedly superimposing material on existing lines) or cryovolcanism (the eruption of material is then frozen solid at the normal surface temperature causing disruption, displacement, and reworking of the crustal ice[11]).

[10] Greenberg, R., P. Geissler, et al. (1998). "Tectonic Processes on europa: Tidal Stresses, Mechanical Response, and Visible Features*1." Icarus **135**(1): 64-78.
[11] Figueredo, P.H. and R. Greeley (2004). "Resurfacing history of Europa from pole-to-pole geological mapping." Icarus **167**(2): 287-312.

Observers interpreted the images from Voyager and Galileo by looking at the shadows and changes in color of Europa's surface. Basically the shadows indicate elevation and the colors indicate different grain size or different material composition. The age of the surface material is estimated by looking at the intersections of different surface features: the fewer the interruptions (ridges, craters, etc), the younger the surface feature.

4.1 Plains

Relatively smooth areas broken into patterns make up the plains that are the most common characteristic surface feature on Europa (Figure 4.1.1)[12]. Plains are distinguished by a collage of relatively smooth, bright, uniform colored ice broken by wedges and bands of darker or lighter materials. With the images we have, the disruptions can be 'removed' and the puzzle solved to determine what the initial surface looked like (Figure 4.1.2).

Figure 4.1.1: Europa's Icy Plains: The bluish background colors are the plains and the redish and white lines are other surface features.

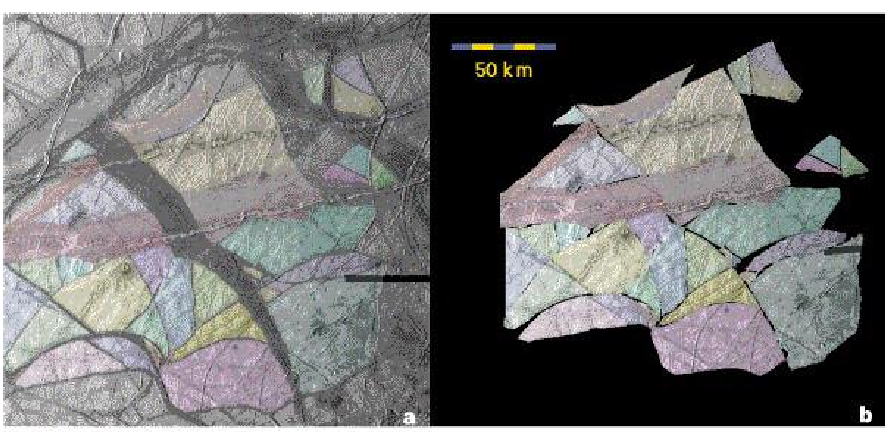


Figure 4.1.2: A "solved" plain puzzle on Europa: The darker, newer lines that cover the brightly colored areas on the left were removed so the older surface features could be pieced back together as seen on the right side.[13]

[12] NASA's JPL Photojournal on Europa: http://photojournal.jpl.nasa.gov/catalog/PIA00275
[13] Sullivan, R. e. a. (1998). Episodic plate separation and fracture infill on the surface of Europa. Nature. **391**: 371-373.

These wedges and bands appear in many different sizes and sometimes in groups that form a pattern. Plains are possibly formed by Europa's surface being stretched such that material shifts around and possibly wells up from below the ice layer.

4.2 Mottled Terrain

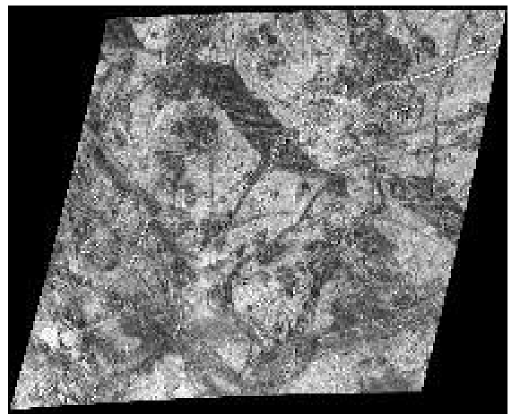


Figure 4.2.1: Europa's Mottled Terrain[14]: the different colors indicate different textures, elevation, and materials.

Mottled terrain is comprised of a "dense population of spots and patches of dark material ranging in size from a few tens of kilometers down to the resolution limit of a few kilometers."[15] It also often has various pits, spots, and domes formed by warmer ice upwelling and disrupting the surface (Figure 4.2.2).

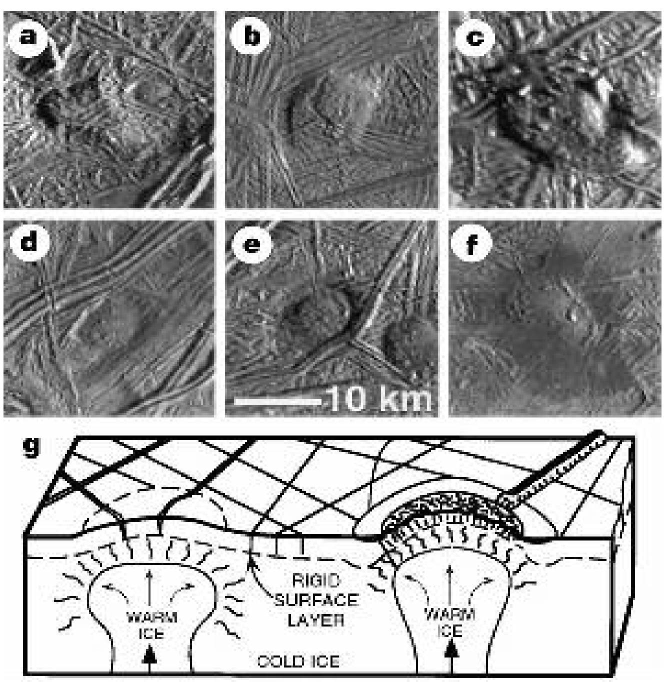


Figure 4.2.2: (a-f) Pits, spots, domes. (g) How warmer ice rising could cause the surface to bulge and create the pits, spots, and domes seen on Europa.[16]

[14] NASA's JPL Photojournal on Europa: http://photojournal.jpl.nasa.gov/catalog/PIA01401
[15] Morrison, D. (1940). Exploring Planetary Worlds. New York, Scientific American Library.
[16] Pappalardo, R. T. e. a. (1998). Geological evidence for solid-state convection in Europa's ice shell. Nature. **391**: 365-368.

4.3 Bands and Lines

Europa's surface is covered in a random spiderweb of bands and lines (Figure 4.3.1). Subsurface material welling up through a crack in the surface (Figure 4.3.2) generally makes the bands and lines that crisscross all over Europa's surface. Thus most of these bands and lines are comprised of smaller ridges running the length of the band (Figure 4.3.3).

Figure 4.3.1: Europa's Bands and Lines[17]: The dark colors are the bands and lines and the lighter color is a relatively smooth plains.

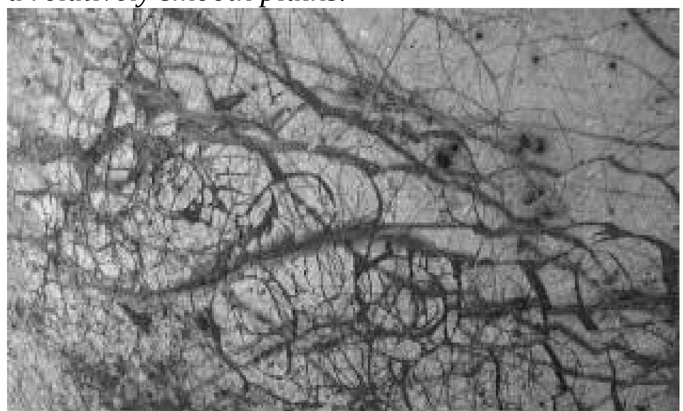
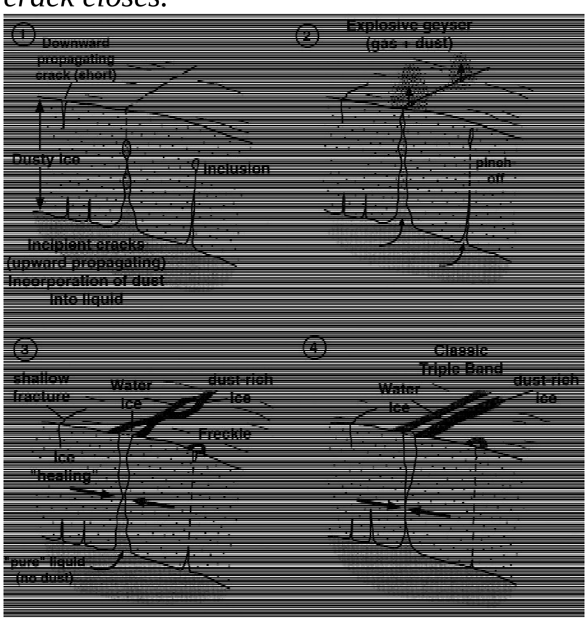


Figure 4.3.2: A Model of Band and Line Formation: Crack opens, material wells up, crack closes.[19]



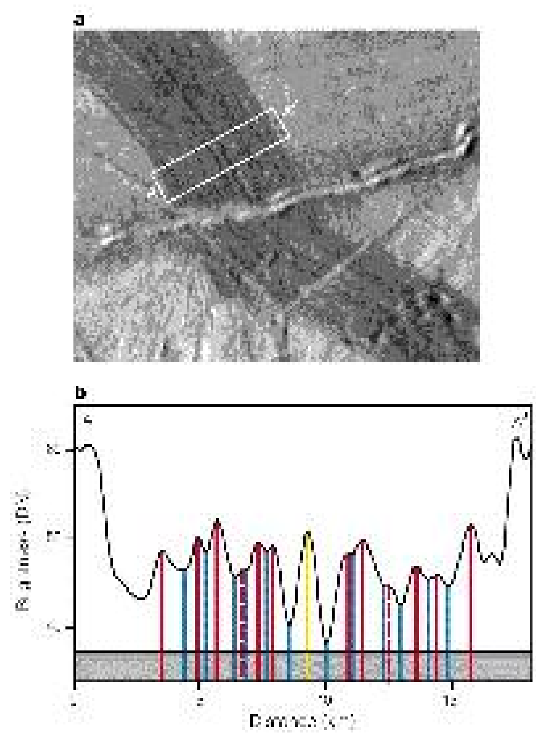


Figure 4.3.3: Ridges of Bands[18]: (a) A picture of a band with a rectangular section blocked off. (b) The rectangular section turned on its side and blown up to show the different elevations and ridges present in such bands.

[17] NASA's JPL Photojournal on Europa: http://photojournal.jpl.nasa.gov/catalog/PIA00578
[18] Sullivan, R. e. a. (1998). Episodic plate separation and fracture infill on the surface of Europa. Nature. **391**:371-373.
[19] Greeley, R., R. Sullivan, et al. (1998). "Europa: Initial Galileo Geological Observations*1." Icarus **135**(1): 4-24.

4.4 Ridges and Troughs

Figure 4.4.1: Europa's Ridges and Troughs[20]: Generally each pair of ridges has a trough between them.

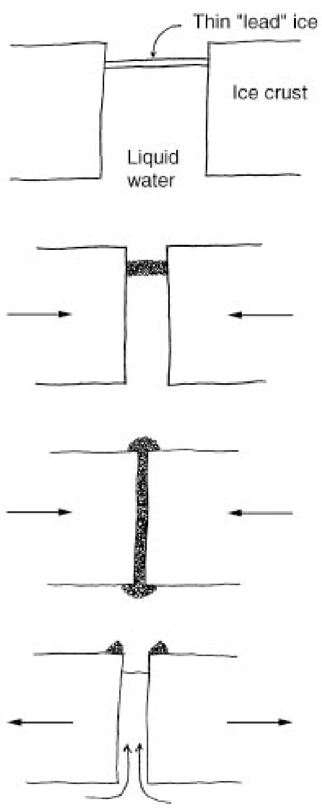
Ridges and troughs are one of the main features that distinguish a full moon image of Europa from the other Galilean moons. They seem to cut across each other randomly. There are images of many ridges, which have been categorized into five types:[21]

1. simple pairs of ridges about 100 m high and 1 km wide with 1 km between them
2. wider ridges, symmetrical on both sides of a central valley lineated length-wise such that they look like multiple subridges with elevations less than 200 m
3. large-scale global lineaments of braided, intertwined, mutually crossing ridge complexes comprised of simple pairs and wider pairs
4. cycloidal ridges: chains of segments joined at cusps into a cycloidal pattern
5. "triple bands" are types 2 and 3 bordered by diffuse regions of darker surface material

Ridges are created as Europa's surface is repeatedly squeezed, stretched, and compressed by its changing tidal deformation in its orbit such that cracks in the ice layer open and close (Figure 4.4.2). When cracks open the subsurface material rises to the surface and freezes. Then when the crack closes, the newly frozen material is crushed and some is pushed out of either end of the crack. When the crack opens again the bunch of crushed ice that was pushed to the top splits to form a little ridge on either side of the reopened crack. Multiple repetitions of this process and a large crack opening contribute to increasing the size of ridges. Layers, comprised

[20] NASA's JPL Photojournal on Europa: http://photojournal.jpl.nasa.gov/catalog/PIA01179
[21] Greenberg, R., P. Geissler, et al. (1998). "Tectonic Processes on Europa: Tidal Stresses, mechanical Response, and Visible Features*1." Icarus. **135**(1): 64-78.

of multiple ridges with different heights, are formed by variations in this process that push more or less frozen material to the surface at a given time. Crisscrossing ridges form when the cracks migrate or when different ones open and close at different times. This process of ridge formation creates troughs between ridges and sometimes the weight of the ridges causes the crust to warp downwards.



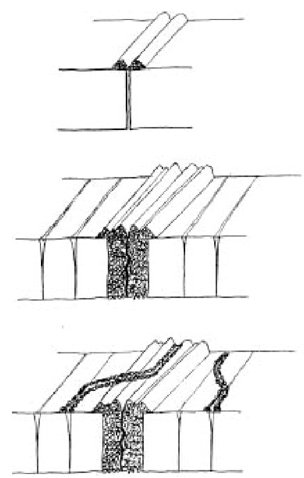


Figure 4.4.2: Ridge and Trough Formation:
Surface stresses open a crack that fills with the material from below. The surface of the fresh material freezes. As the crack closes the frozen material increases, fills the crack and spills out at either opening. The next time the crack opens there are little ridges on either side of the opening. Over time a bunch of different sized ridges accumulate. The cracks also change over time so that the ridges and troughs crisscross each other.[22]

4.5 Craters

Impact craters are circular features created by objects from space hitting Europa. Some craters radiate waves of ridges and/or changing bands of color while others spray a circle of material around the impact center. Many of the craters have peaks or ridges inside the center impact areas as seen in Figure 4.5.2.

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[22] Greenberg, R., P. Geissler, et al. (1998). “Tectonic Processes on Europa: Tidal Stresses, mechanical Response, and Visible Features*1.” Icarus. **135**(1): 64-78.

Figure 4.5.1: Europa's Craters[23] have many different impact patterns

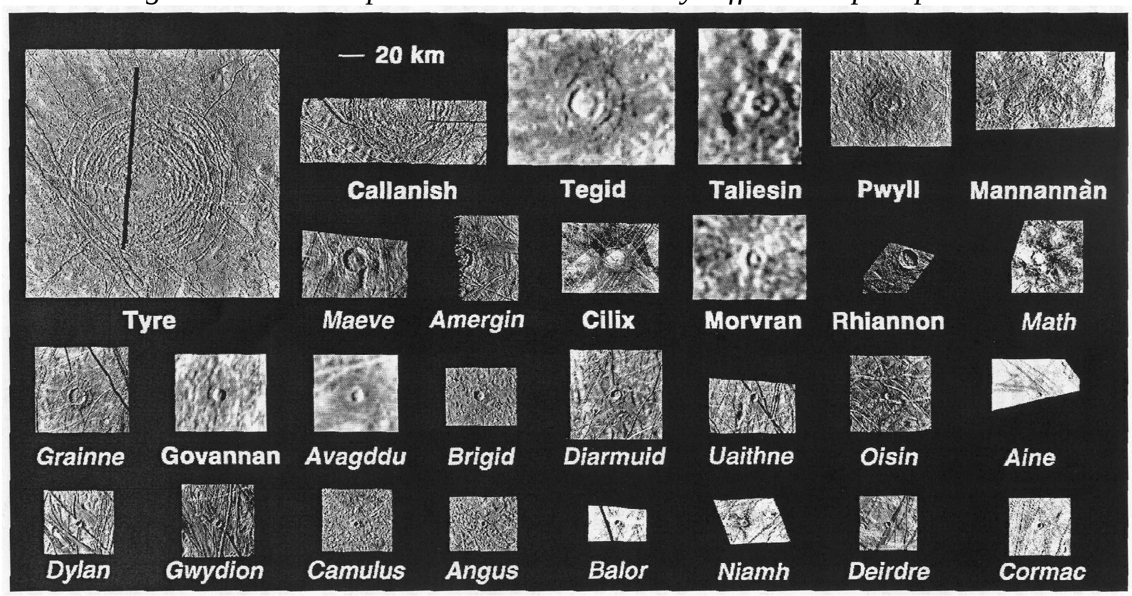


Figure 4.5.2: This Impact Crater Topography (left side) of three impact craters (right side) shows that they all have a central peak and various other ridges.[24]

[23] Moore, J.M., E. asphaug, et al. (2001). "Impact Features on europa: Results of the Galileo Europa Mission (GEM)." Icarus. **151**: 93-111.

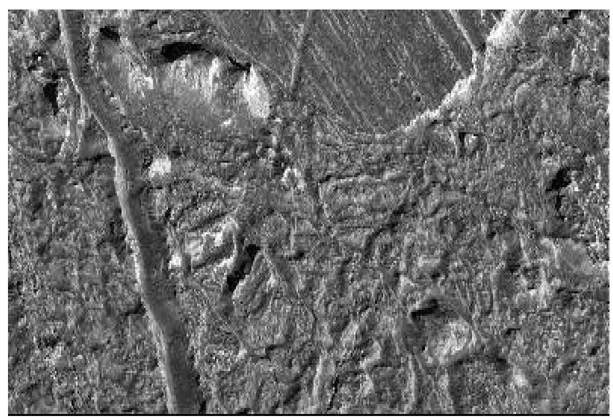
[24] Moore, J.M., E. asphaug, et al. (2001). "Impact Features on europa: Results of the Galileo Europa Mission (GEM)." Icarus. **151**: 93-111.

One way to estimate the age of surfaces in space is by the number visible impact craters. Based on Europa position in the Jovian system and the amount of impact craters on Io and Ganymede, there should be significantly more impact craters on Europa. Thus Europa is considered to have a relatively young surface of about 10^8 years old,[1] which has covered up most of its old impact craters.

4.6 Chaotic Terrain

Chaotic Terrain (Figure 4.6.1) is the surface that looks busy and has no recognizable patterns, except in terms of type of chaotic terrain. Scattered around its surface, Europa has various flows of more recent material covering up older surface characteristics. The welling up of warmer subsurface material and the refreezing into some sort of matrix (an uneven surface of material frozen at different times) at the surface (Figure 4.6.2) creates most of Europa's chaotic features. Often times on Europa's surface there are ridges running through or along side of chaotic area because of where the subsurface material happened to raise up (Figure 4.6.3).

Figure 4.6.1: Chaotic Terrain on Europa[25] is basically random terrain areas with different shapes intertwined without a unifying pattern.



[25] NASA's JPL Photojournal on Europa: http://photojournal.jpl.nasa.gov/catalog/PIA01177

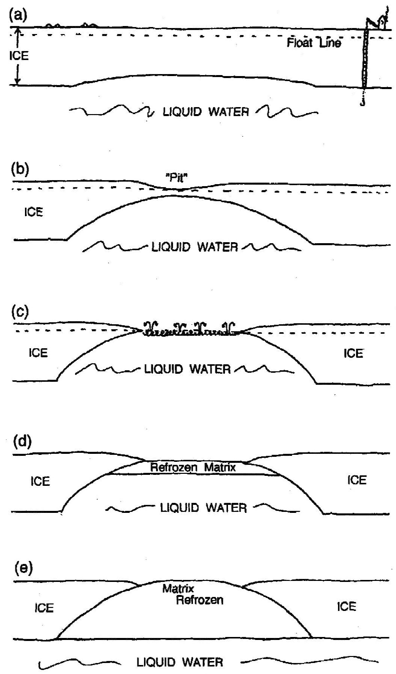


Figure 4.6.2: A Model for Chaos Formation: Water wells up and refreezes in shapes with no pattern.[26]

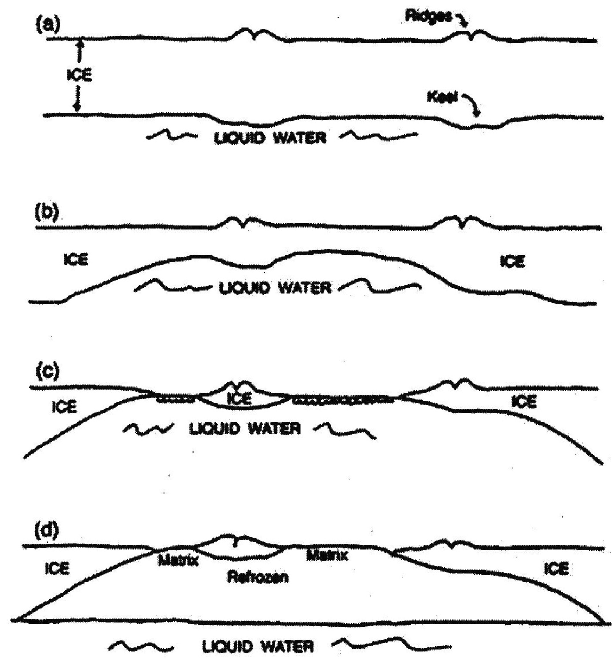


Figure 4.6.3: A Model for Ridges Near and in Chaotic Terrain: Chaotic features form around or near ridges[27]

4.7 Icebergs and Buoyancy

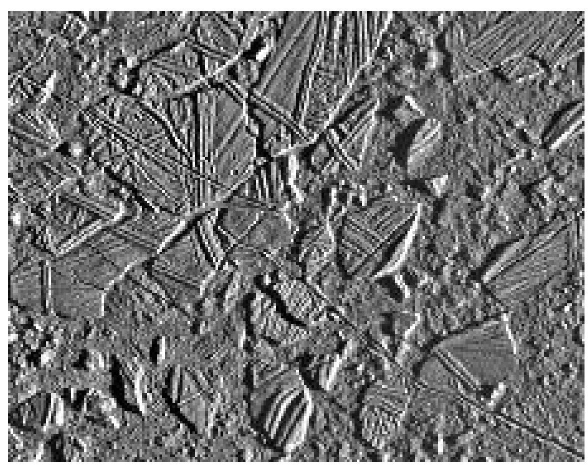


Figure 4.7.1: Europa's Icebergs[28]

These chaotic areas of broken chunks of ice are yet another famous distinguishing characteristic of Europa's surface. These ice rafts look very similar to the icebergs we have here on Earth. Thus they are probably also caused by the thawing, breaking, moving, and refreezing of the surface layer of ice (Figure 4.7.2).

[26] Greenberg R., g. V. Hoppa, et al. (1999). "Chaos on Europa." Icarus **141**(2): 263-286.
[27] Greenberg R., g. V. Hoppa, et al. (1999). "Chaos on Europa." Icarus **141**(2): 263-286.
[28] NASA's JPL Photojournal on Europa: http://photojournal.jpl.nasa.gov/catalog/PIA00591

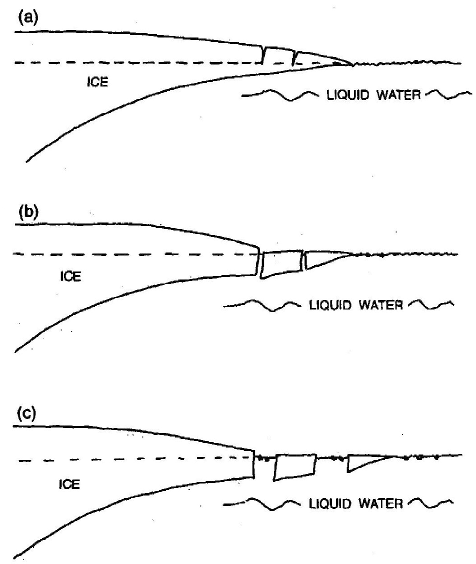


Figure 4.7.2: A Model of Iceberg Formation: The surface ice layer thins and then opens so the material from below is at the surface. Then the ice sometimes fractures off into an opening of movable subsurface material and creates a Europan iceberg.[29]

Icebergs are special because their buoyancy can be used to estimate the thickness of the icy surface layer. For example, say we have some random sized floating chunk of ice, m_{chunk} (Figure 4.7.2) with a distance *d* below the surface and a total thickness of length *l*. When the chunk is floating in equilibrium, the pressure from the water beneath it pushes up on the chunk and the force of gravity pulls it down.

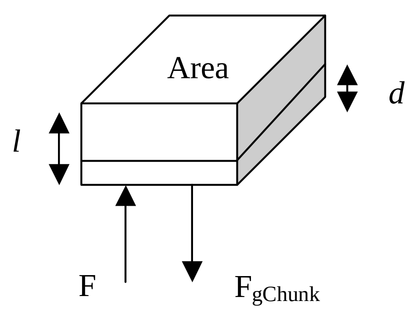


Figure 4.7.2: Dimensions of a floating ice chunk and the forces acting on it, where d is the length beneath water and F_{gChunk} is the weight of the chunk.

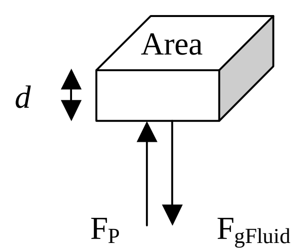


Figure 4.7.3: Dimensions of water displaced by the floating ice chunk (treated like a chunk with its top flush with the surface), where F_{gFluid} is the weight of the displaced fluid.

Archimedes Principle says that the pressure of the water pushing the chunk up is equal to the weight of the displaced fluid. The displaced fluid can be treated like a chunk with its top flush with the surface so that it has the same upward pressure and downward pull of gravity (Figure 4.7.3). Manipulating Newton's Second Law of Motion produces equations for the pressure acting on the chunk and the displaced water:

[29] Greenberg R., g. V. Hoppa, et al. (1999). "Chaos on Europa." Icarus **141**(2): 263-286.

Ice Chunk

$$\Sigma F = ma$$
$$a = 0$$
$$\Sigma F = \left|\vec{F}_p\right| - \left|\vec{F}_g\right| = 0$$
$$\left|\vec{F}_p\right| = \left|\vec{F}_g\right|$$
$$\left|\vec{F}_p\right| = PA$$
$$\left|\vec{F}_g\right| = mg \qquad \text{(Eq 4.7.1)}$$
$$PA = m_{chunk}\, g$$
$$m = \rho_{chunk}\, Al$$
$$P = \frac{m_{chunk}\, g}{A}$$
$$P = \rho_{chunk}\, gl$$

Displaced Water

$$\Sigma F_{OnFluid} = ma$$
$$a = 0$$
$$\Sigma F_{OnFluid} = \left|\vec{F}_p\right| - \left|\vec{F}_{gFluid}\right| = 0$$
$$\left|\vec{F}_p(d)\right| = \left|\vec{F}_{gFluid}\right|$$
$$F_p(d) = P(d)A = m_{fluid}g$$
$$F_{gFluid} = m_{fluid}g = \rho_{fluid}Adg \qquad \text{(Eq 4.7.2)}$$
$$P(d)A = \rho_{fluid}Adg$$
$$P(d) = \rho_{fluid}gd$$

where $\vec{F}_p(d)$ is the force due to pressure at *d* below the surface and *P(d)* is the pressure at *d* below the surface. Setting $P = \rho_{chunk}gl$ equal to $P(d) = \rho_{fluid}gd$ and reducing the new equation shows that the ratio *d/l* is proportional to the density of the chunk divided by the density of the fluid:

$$\frac{d}{l} = \frac{\rho_{chunk}}{\rho_{fluid}}. \qquad (4.7.3)$$

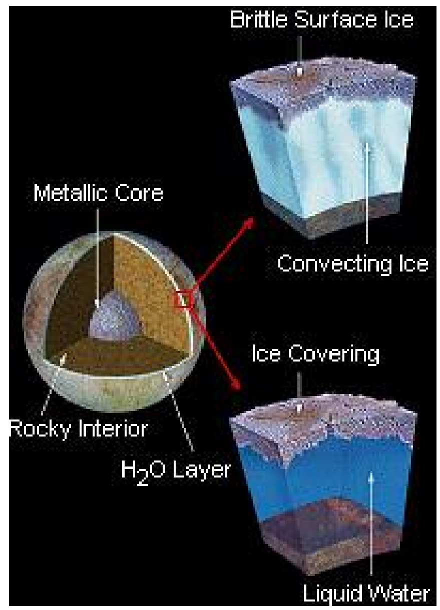
From images of Europa, estimates of surface feature heights have been made so we have a value *k* = *l*-*d*, which is equivalent to *l*(1-*d/l*) such that

$$l = \frac{k}{\left(1 - \frac{d}{l}\right)} = \frac{k}{1 - \frac{\rho_{chunk}}{\rho_{fluid}}}. \qquad (4.7.4)$$

To get a high estimate numerical value, plug in *k*=900m, chunk density is approximately that of regular ice, 0.91 g/cm^3, and the density of the fluid is approximately that of salty ocean water, 1.027 g/cm^3. Plugged in, these numbers result in a maximum iceberg length of about 8 kilometers. The estimated height of 900 meters is about one kilometer so that means that the maximum ice layer below the surface for a floating chunk of ice is about 7 kilometers. However, the actual ice layer is probably thicker as seen in Figure 4.7.2.

5. Interior

Figure 5.1: Two views of Europa's Interior: moveable ice or liquid water.[30]



Europa's density and moment of inertia estimates from spacecraft data implies that Europa is comprised of a metallic core and a rocky dehydrated mantle that take up about 92% of Europa's mass. Europa's moment of inertia (how mass is distributed) ratio $\frac{I}{MR^2} = 0.347 \pm 0.014$ suggests a "differentiated centrally condensed body."[31] The surface layer is an approximately 100-140km (60-84 miles) thick crust of water ice. Thus Europa's outer layers are thought to consist of either liquid water or convecting, movable ice under the brittle surface ice covering. The Galileo spacecraft's magnetometer data of the surrounding magnetic field also suggested the existence of a salty ocean.

6. Magnetic Fields

The Galileo spacecraft observed that the magnetic field around Europa is different from the value of Jupiter's normal dipole magnetic field at the location of Europa. Jupiter's magnetic field is caused by a dynamo process. In order to produce a dynamo-induced magnetic field, an object requires certain conditions: there must exist a pre-existing magnetic field, the object must

[30] NASA's JPL Photojournal on Europa: http://photojournal.jpl.nasa.gov/catalog/PIA01669
[31] Imke de and Jack Lissauer Pater, *Planetary Science*. (Cambridge University Press, Cambridge, 2001).

be spinning, and it must have an internal heat source surrounded by convecting and conducting material. These four characteristics create moving charges and currents that create the resulting magnetic field.[32] The exact details of how a dynamo produces a magnetic field are very complicated; basic explanations of the process can be found in a number of texts.[33] Basically a dynamo magnetic field occurs because the existing magnetic field lines get twisted up, causing currents to flow. The twisted field lines continue to wrap around creating additional currents, thus producing a magnified magnetic field that is self-sustaining and long lasting. Earth and the Sun also have magnetic fields created by this dynamo process.

Jupiter's dynamo produces a magnetic field that has a magnetic axis is tilted about 10° from its rotation axis, like Earth's, so it is not a simple dipole (Figure 6.1). Thus Jupiter's equatorial plane and magnetic equatorial plane are also tilted (Figure 6.2).

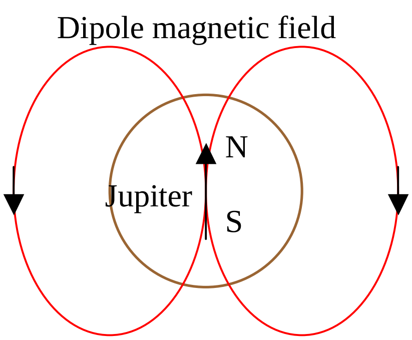


Figure 6.1: A Plain Old Dipole Magnetic Field

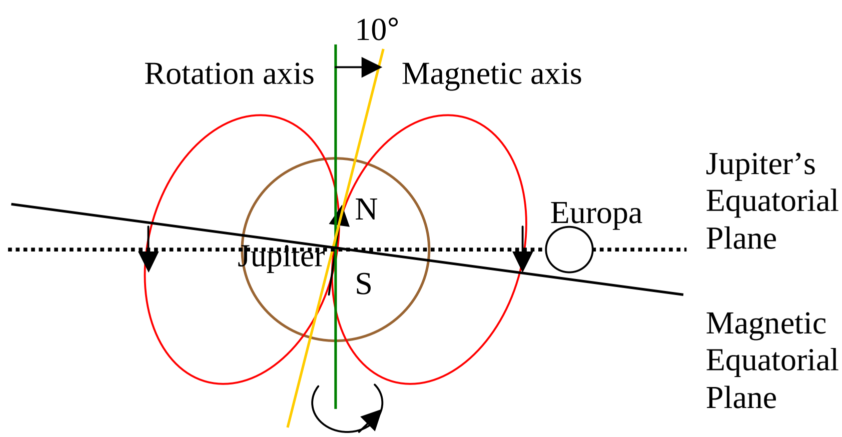


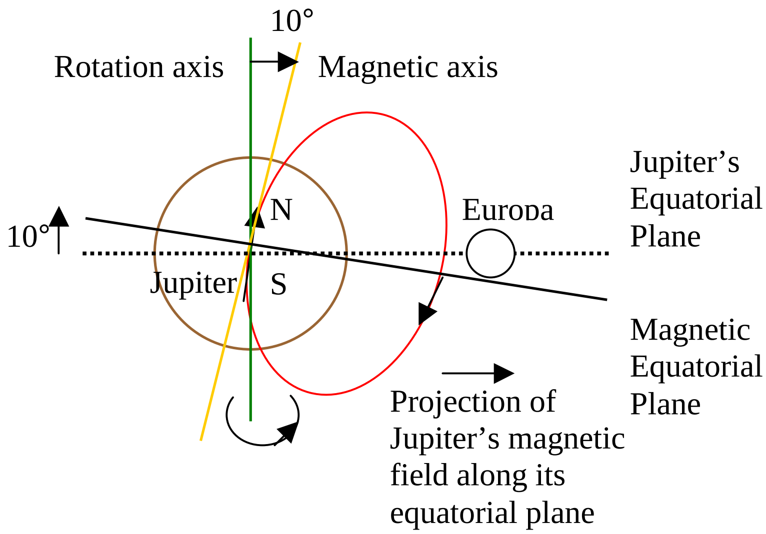
Figure 6.2: Jupiter's Magnetic Field

That slight tilt causes the projection of Jupiter's magnetic field along its equatorial plane to change as Jupiter's magnetic axis rotates around its polar axis. This is important for Europa since it orbits in Jupiter's equatorial plane. The component of Jupiter's magnetic field that is

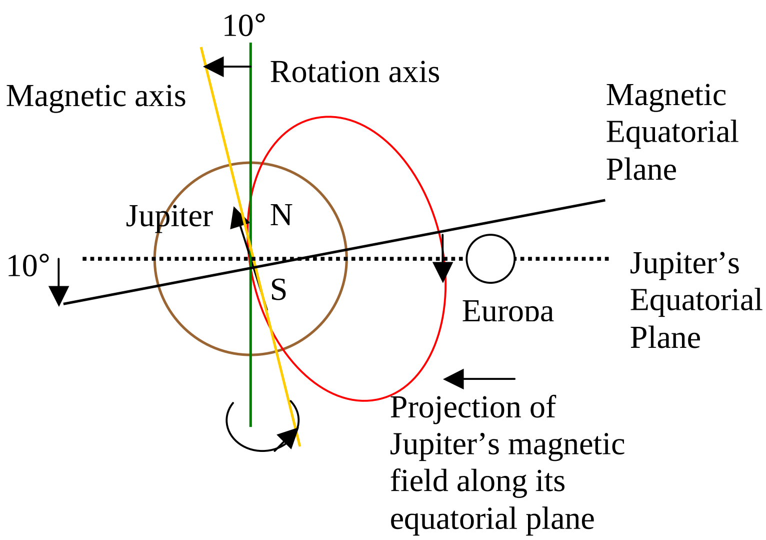
[32] Ampere's and Biot-Savart Laws
[33] Imke de and Jack Lissauer Pater, *Planetary Science*. (Cambridge University Press, Cambridge, 2001) pg 301-303.

perpendicular to Europa's orbital plane basically points downward. However, the component parallel to the plane oscillates back and forth as Jupiter rotates (Figure 6.3).

Figure 6.3: Changing projection of Jupiter's rotating magnetic field.



(a) When Jupiter's magnetic axis is tilted towards Europa, the projection of Jupiter's magnetic field along the equatorial plane is towards Europa.



(b) Half a rotation period later (about 5.5 hours) when Jupiter's magnetic axis is tilted away from Europa, the projection of Jupiter's magnetic field along the equatorial plane is away from Europa.

The Galileo spacecraft observations showed that magnetic field near Europa is different based on a field predicted solely from Jupiter's field. Subtracting the predicted field from the observed field revealed a projected field that pointed opposite that of Jupiter's projected field in

Europa's orbit. The change in projection of Jupiter's magnetic field around Europa prompted the question: Does Europa have its own dipolar dynamo magnetic field or is Europa's magnetic field the result of Jupiter's changing field creating an opposite field[34] by inducing a current in some conductive material[35] on Europa? At one point the Galileo spacecraft happened to pass by Europa when Jupiter's magnetic field projection was opposite what it had been on all the other passes. Europa's field was found to be still projected opposite Jupiter's field. Thus it was concluded that Europa's magnetic field is induced by the change in Jupiter's magnetic flux as Jupiter rotates. In order for this to occur there must be some sort of conducting material in Europa that allows the induced currents in Europa to produce a magnetic field. Europa's surface features indicate some sort of liquid or movable material under the surface ice layer and one of the best conductors is salt water so it is logical to conclude that Europa may have a slushy or liquid salty ocean.

7. Atmosphere

Further evidence to support the salty ocean theory is that the Galileo spacecraft found a tenuous oxygen atmosphere on Europa. An atmosphere exists when the escape velocity (calculated from the Law of Conservation of Energy) is much greater than the particle's thermal velocity (calculated in the same way using the thermodynamic equation of thermal kinetic energy, where *k* is the Boltzman's constant).

[34] Lenz's Law: an induced current is always directed opposite of the change in magnetic flux creating it
[35] Faraday's Law: a change in the magnetic flux through a conducting material induces a magnetic field in the material

$$E_{total} = PE + KE = 0$$
$$\frac{1}{2}mv^2 = \frac{GMm}{r}$$
$$v_{escape} = \sqrt{\frac{2GM}{r}} = \sqrt{\frac{2GM_E}{R_E}}$$
$$= 202m/\sec \qquad (7.1)$$

$$E_{thermalKE} = \frac{mv^2}{2} = \frac{3}{2}kT$$
$$\frac{1}{2}m_{particle}v_{thermal}^2 = \frac{3}{2}kT \qquad (7.2)$$
$$v_{thermal} = \sqrt{\frac{3kT}{m_{particle}}}$$

$$v_{thermalHydrogen} = \sqrt{\frac{3kT}{m_{hydrogen}}} = \sqrt{\frac{3(1.38*10^{-23}J/K)(110.778K)}{1*1.67*10^{-27}kg}} = 1657m/\sec \qquad 7.3$$

$$v_{thermalOxygen} = \sqrt{\frac{3kT}{m_{oxygen}}} = \sqrt{\frac{3(1.38*10^{-23}J/K)(110.778K)}{16*1.67*10^{-27}kg}} = 414.3m/\sec \qquad 7.4$$

Hydrogen's thermal velocity (Equation 7.3) is bigger than oxygen's (Equation 7.4) so it makes sense that hydrogen escapes and oxygen remains to form an atmosphere. An atmosphere is retained when $v_{escape} \geq 10v_{thermal}$, where "the factor of 10 takes into account the high-speed tail of the Maxwellian distribution of speeds."[36] Thus both the hydrogen and oxygen escape Europa's surface but hydrogen leaves faster than oxygen. It is thought that the oxygen atmosphere might come from a 'sputtering process' where H_20 molecules are knocked off of Europa's surface such that there is thought to be a surface pressure of molecular oxygen of about 10^{-11} bar.[37] Thus it makes sense for there to be a slight oxygen atmosphere on Europa because the components of the water particles being knocked off Europa's surface constantly replace those that escape.

[36] Zeilik and Smith, Introductory Astronomy & Astrophysics, Second Edition, pg 29.
[37] Imke de and Jack Lissauer Pater, *Planetary Science*. (Cambridge University Press, Cambridge, 2001).

8. Future Missions

Figure 8.1: An Artist's depiction of a possible Europa ocean probe and what it might find[38]

There are many proposals for future missions, all with the same goal of gathering more data. One is to send a robotic probe down to Europa's surface to physically gather data and information and to explore the possible subsurface ocean.[39] In order to explore the subsurface ocean the probe must first get to it. Some proposals assume the probe would be able to access a crack in the surface ice and simply plop itself into the subsurface ocean. Others propose having the probe heat or grind its way through the ice, which would be quite the task when that ice could be anywhere around 100 km thick. Another data gathering proposal is to fly a probe through particle clouds created by specially designed pieces of material that the probe sends down to impact Europa's surface.[40] Currently the proposal for the spaceship to get such probes to Europa is basically powered by more nuclear energy than has ever been launched from Earth before. However, despite the excitement about Europa, no proposals have been funded yet.

[38] http://klx.com/europa/

[39] Di Pippo, S., R. Mugnuolo, et al. (1999). "the exploitation of Europa ice and water basins:: an assessment on required technological developments, on system design approaches and on relevant expected benefits to space and Earth based activities." Planetary and pace Science **47**(6-7): 921-933.

[40] NASA's Europa Ice Clipper Proposal, http://www.astrobiology.com/europa/ice.clipper.html

9. Conclusions

Observations of Europa have determined many of its distinguishing characteristics, like surface features and induced magnetic field, and analyses of those observations indicate how Europa's characteristics were created. Such observations have changed and improved over the years as technology improved. Our understanding of Europa's orbit is one such example. At first it was thought that Europa had a circular orbit tidally locked on Jupiter in to synchronous rotation. More recent observations showed that Europa actually has a slight eccentricity due to orbital resonance with its nearest neighbors: Io and Ganymede. It was determined that Europa's slight eccentricity along with the tides produced by Jupiter's gravitational pull on Europa, cause enough surface stress and heating to create Europa's fascinating surface features that resemble our own Earth's frozen oceans. Recent observations done by the Galileo spacecraft indicated that Europa has a magnetic field induced by the change in flux of Jupiter's magnetic field. Additionally, observations found a small oxygen atmosphere on Europa. All of these observations, from surface features to interior composition and magnetic field, support the idea that Europa may have a liquid salty ocean under its surface ice layer. Liquid water is an indicator of possible life, so of course many people, from all walks of life, are anxious to obtain first hand observations from Europa by sending a probe of some sort to physically gather such data. Thus Europa, Jupiter's second Galilean moon, has a fascinating story of how we came to know it as it is and a fascinating future of more discovery yet to come.

10. Appendix A

Table A.1:
Imaging Instruments of the Galileo Spacecraft:[41] *What they look like and what they accomplish.*

Name	Picture	Purpose
Solid State Imaging (SSI)		Galilean satellites, high resolution, atmospheric small-scale dynamics
Near-Infrared Mapping Spectrometer (NIMS)		Surface/atmospheric composition thermal mapping
Photopolarimeter-Radiometer (PPR)		Atmospheric particles, thermal/reflected radiation
(Extreme) Ultraviolet Spectrometer UVS/EUVS	QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.	Atmospheric gases, aerosols, etc.
Magnetometer (MAG)		Strength and fluctuations of magnetic fields
Energetic Particles Detector (EPD)		Electrons, protons, heavy ions
Plasma Subsystem (PLS)		Composition, energy, distribution of ions
Plasma Wave Subsystem (PWS)		Electromagnetic waves and wave particle interactions
Dust Detector Subsystem (DDS)		Mass, velocity, charge of submicrometer particles
Heavy Ion Counter (HIC)		Spacecraft charged-particle environment
Celestial Mechanics		Masses and internal structures of bodies from spacecraft tracking
Propagation		Jupiter/Satellite radii and atmospheric structure from radio propagation

[41] This table is adapted from http://www.jpl.nasa.gov/galileo/gem/fact.html

11. Annotated Bibliography

David Morrison, *Exploring Planetary Worlds*. (Scientific American Library, New York, 1940).

This has awesome background astronomy information with some specifics on Europa.

Richard Greenberg, Paul Geissler, Gregory Hoppa et al., Icarus **135** (1), 64 (1998).

Good explanations of tidal deformations and resulting surface formation processes.

Patricio H. Figueredo and Ronald Greeley, Icarus **167** (2), 287 (2004).

Describes surface features and how they were formed based on Galileo spacecraft data.

R. et all Sullivan, in *Nature* (1998), Vol. 391, pp. 371.

Explains Europa's puzzle-like surface and multiple ridge lines.

R. T. et all Pappalardo, in *Nature* (1998), Vol. 391, pp. 365.

Good explanations of Europa's surface features.

Ronald Greeley, Robert Sullivan, James Klemaszewski et al., Icarus **135** (1), 4 (1998).

This is a great source of scientific level background information on Europa.

Jeffrey M. Moore, Erik Asphaug, Michael J. S. Belton et al., Icarus **151** (1), 93 (2001).

All about Europa's craters.

Richard Greenberg, Gregory V. Hoppa, B. R. Tufts et al., Icarus **141** (2), 263 (1999).

All about Europa's chaotic terrain.

Imke de and Jack Lissauer Pater, *Planetary Science*. (Cambridge University Press, Cambridge, 2001).

Fabulous source of the physics involved in the study of bodies in space.

Simonetta Di Pippo, Raffaele Mugnuolo, Paolo Vielmo et al., Planetary and Space Science **47** (6-7), 921 (1999).

This is a proposal for a possible future mission to Europa.