Exploring Europa: Science from the Jupiter Europa Orbiter—A Future Outer Planet Flagship Mission

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The Europa Jupiter System Mission, an international joint mission recently studied by NASA and the European Space Agency, would directly address the origin and evolution of satellite systems and the water-rich environments of icy moons. In this article, we report on the scientific goals of the NASA-led part of the Europa Jupiter System Mission, the Jupiter Europa Orbiter, which would investigate the potential habitability of the ocean-bearing moon Europa by characterizing the geophysical, compositional, geological, and external processes that affect this icy world.

INTRODUCTION

About 400 years ago Galileo Galilei discovered the four large moons of Jupiter, thereby spurring the Copernican Revolution and forever changing our understanding of the universe. Today, these Galilean satellites may hold the key to understanding the habitability of icy worlds, as three of the moons are believed to harbor internal oceans. On Earth, water is the key ingredient for life, so it is reasonable that the search for life in our solar system should focus on the search for water. The Jovian system is also important to understanding how satellites form and evolve around giant planets; Jupiter is thought to be the archetype for giant planets orbiting other stars. The Voyager spacecraft flew through the Jupiter system in 1979, sending back the first data from these moons and revealing for the first time the tremendous variations among them.[1] Exploration of the system continued in 1994 with the arrival of the Galileo spacecraft. After dropping a probe into Jupiter's atmosphere, the spacecraft spent several years orbiting the giant planet, accomplishing flybys of all the Galilean satellites, Io, Europa, Ganymede, and Callisto. Despite significant technical setbacks, including the loss of the main communication antenna and issues with the onboard tape recorder, the spacecraft returned valuable data that significantly increased our understanding of the moons. Perhaps the most significant discovery was that Europa probably contains a salty near-surface ocean, thereby revealing a potential habitat for life.

Over the past decade, the high astrobiological potential of Europa has been recognized by a variety of groups, including NASA and the National Research Council (NRC). The last NRC Planetary Decadal Survey[2] recommended a Europa orbiter flagship mission as the number one priority for solar system exploration over the next decade. Because of the severe technical challenges inherent in flying such a mission, NASA did not implement this recommendation, although numerous studies have examined the feasibility of a mission to Europa.

In 2007, NASA commissioned four flagship mission studies to investigate the potential science return from (*i*) the Jupiter system, (*ii*) Europa, (*iii*) Saturn's moon Titan, and (*iv*) Saturn's moon Enceladus. The studies were led by APL (Titan), the Jet Propulsion Laboratory (JPL) (Europa and the Jupiter system), and the NASA Goddard Space Flight Center (Enceladus). Simultaneously, a Europa and Jupiter system mission, Laplace, was proposed to the European Space Agency (ESA) in response to a call for proposals for their Cosmic Vision program. In 2008, two of these studies—Europa and Titan—were selected for further investigation by joint JPL/APL teams. One JPL/APL team worked with ESA to define a joint mission to Europa and the Jupiter system, named the Europa Jupiter System Mission (EJSM), comprising the NASA Europa mission and the ESA Laplace orbiter. In early 2009, although both Europa and Titan were deemed to have high scientific value, EJSM was chosen by NASA to be the next flagship mission once funds became available because of its lower perceived risk.

EJSM would consist of two sister spacecraft (Fig. 1): the Jupiter Europa Orbiter (JEO), led by NASA, and the Jupiter Ganymede Orbiter (JGO), led by ESA.[3] Both spacecraft would launch in 2020 and would arrive in the Jovian system in 2026. Each would spend approximately 2.5 years orbiting Jupiter and making measurements of all four Galilean satellites as well as Jupiter's weather, its rings and magnetic field, and its small, irregular satellites. In 2028, JEO would enter a circular orbit around Europa where it would spend 9 months investigating the moon's geology, interior structure, ice shell, composition, and local environment. At about the same time, JGO would go into orbit around Ganymede for a similar amount of time. Because both spacecraft would be in the Jovian system at the same time, there is the potential for unprecedented synergistic science.

Throughout 2009 and 2010, APL and JPL worked on the details of the design and implementation of JEO. NASA continued to fund the study at a low level, and risks continued to be mitigated, but the mission was not fully funded for implementation. At the time of this writing, a new NASA-commissioned NRC Planetary Decadal Survey, which lays out the priorities for solar system exploration for the next decade, has just been released. NASA leadership made it clear that, for JEO to proceed, it would need to have a strong endorsement from the Planetary Decadal Survey. Although the newly released 2011 Planetary Decadal Survey confirmed the importance of a mission to Europa, because of the current economic situation and its effect on the NASA budget, no funding is expected for a Europa mission in the next decade unless the cost of the mission can be significantly reduced and Congress can find new funds.[4] Studies of potential descoped missions have just been initiated by NASA. On the ESA side, JGO is in competition with two other missions that are part of ESA's Cosmic Vision program, and it will be another 2 years before the final selection will be made. Even if JGO is not ultimately selected, the science from JEO would stand alone as making groundbreaking contributions to our understanding of how habitable worlds evolve around giant planets. In this article, we focus on the science goals for JEO, as envisaged by the most recent JPL/APL study, before the release of the 2011 Planetary Decadal Survey, and how they would be accomplished.

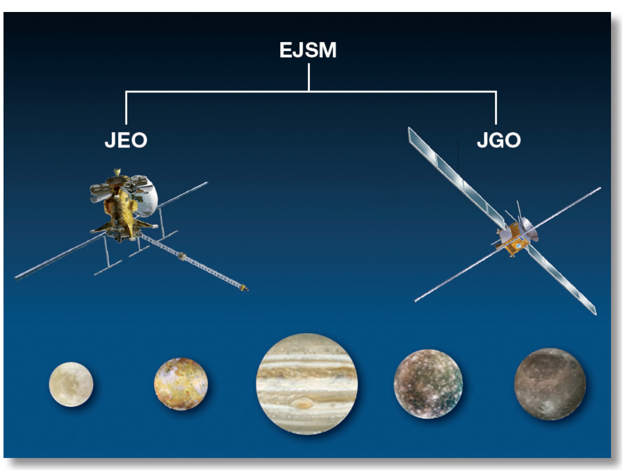

Figure 1. The EJSM consists of two sister spacecraft, NASA's JEO and ESA's JGO. Both spacecraft would explore the Jupiter system: JEO would focus on Europa and Io, and JGO would focus on Ganymede and Callisto. (Image courtesy of NASA/JPL-Caltech.)

SCIENCE BACKGROUND OF JEO

Europa's Ocean and Interior

Europa's icy surface is thought to hide a global subsurface ocean with a volume more than twice that of Earth's oceans. The presence of Europa's ocean is inferred from data collected by the Galileo spacecraft; as the spacecraft traveled through Jupiter's magnetic field, its magnetometer measured changes around Europa consistent with those predicted if a current-carrying outer shell, such as a planet-scale liquid ocean, were present beneath the icy surface.[5] The geological youth (approximately 60 Ma) of the surface of Europa[6] suggests recently active processes operating within the ice shell, probably the result of thermal energy in the shell and a rocky interior driven by tidal heating. Europa's 3.5-day orbit around Jupiter is very slightly elliptical, which means that Jupiter raises tides on Europa, causing the interior to heat up and the surface to flex and fracture. This tidal energy may also drive currents in the ocean.

The structure of Europa is not well known, but most models include an outer ice shell underlain by liquid water, a silicate mantle, and an iron-rich core (Fig. 2).[7] JEO would constrain these models by measuring the gravitational and magnetic fields, the topographic shape, and the rotational state of the satellite. Other measurements such as surface heat flux and local thermal anomalies would also yield information about the satellite's internal heat production and activity, furthering understanding of how tidal heating works in the Jovian system.

JEO would be able to determine whether an ocean is present beneath the surface of Europa by measuring changes in its gravity field and surface topography as it orbits Jupiter. At long wavelengths (hemispherical scales), topography is mainly a response to tides, whereas at intermediate wavelengths (hundreds of kilometers), topographic variations are diagnostic of the thickness and density of the ice shell. Although Europa is quite rough on regional to local scales, it is relatively smooth on a global scale, with no more than approximately 1 km of topographic variation over the mean surface level (in other words, Europa is as smooth as a billiard ball!). If a liquid water ocean is present, the ice shell can deform more easily and the amplitude of the tidal bulge is expected to be approximately 30 m, whereas if no ocean is present, the tidal bulge is predicted to be only approximately 1 m and much harder to discern. JEO would also be able to use gravitational measurements to see whether there are any static anomalies within the shell, such as those that might be found if there were mountains on the ocean floor or if the shell were not uniform in thickness.

Geophysical measurements can also be used to determine the extent of Europa's libration, which occurs because Europa is not in a perfectly circular orbit. (Libration is the process that allows observers on Earth to see the apparent wobble in the hemisphere of the Moon that permanently faces Earth, showing, over a period of time, slightly more than 50% of the lunar surface.) If Europa's ice shell is indeed decoupled from its interior by an ocean, its libration is expected to be three times greater than if the shell behaves rigidly.

Europa is known to respond to the rotating magnetic field of Jupiter through electromagnetic induction.[5,8] This causes eddy currents to be generated on the surface of a conductor—in Europa's case, a fairly conductive briny ocean would generate its own external magnetic field. The measurements made by the Galileo spacecraft's flybys of Europa showed that the measured magnetic signal was in direct response to Jupiter's magnetic field, but the measurements were not able to unambiguously characterize the ocean's thickness or its conductivity. Observations from JEO while in orbit around Europa would significantly improve constraints on our estimates of the conductivity of the ocean, while magnetic soundings at multiple frequencies would be used to determine both conductivity and ocean thickness.

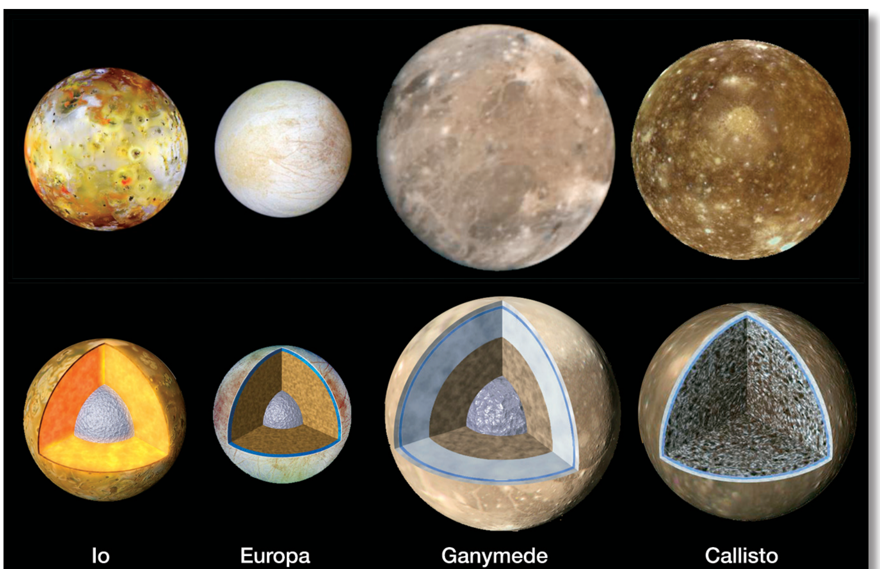

Figure 2. The Galilean satellites, in order of distance from Jupiter (Io is closest). (Upper) The surfaces of the four moons show a tremendous diversity of geological features: rocky Io is covered with recent volcanic deposits and is extremely young; Europa has a very young, icy surface crisscrossed with tectonic lineaments; approximately one-third of Ganymede's icy surface is very old, while the remainder is crosscut by younger swaths of more ice-rich terrain; and Callisto has an ancient surface pockmarked by impact craters. Earth is approximately four times larger than Europa. (Lower) The interiors of the four moons are also very different: Europa, Ganymede, and Callisto are all thought to harbor subsurface oceans (blue), although Europa's ocean is likely to be very close to the surface while Ganymede's and Callisto's are probably deeply buried. Callisto appears to be incompletely differentiated and does not have a core. (Image courtesy of NASA/JPL-Caltech.)

Europa's Ice Shell

Europa's surface has very few impact craters, implying that it is very young and that it may be active today.[6] The processes that have removed traces of older impact craters are not well known, but the shell has undergone significant disruption through fracturing and through some type of cryovolcanism (that is, volcanic processes in which the magma or lava is composed of liquid water and/or slushy ice). The driving forces for these processes result from tidal heating, but the details of how material moves within the ice shell can only be inferred from Galileo data.

Transport of heat from Europa's interior sets the thermal structure of the ice shell. The uppermost several kilometers are cold (Europa's surface temperature averages approximately 100 K), stiff, and thermally conductive. The thickness of this lid is determined by the total amount of heat that must be transported through it and is therefore a constraint on the heat produced in the interior. If the ice shell is thick enough, the lower part is likely to be warmer and convecting (Fig. 3, right). A diapir is a type of intrusion in which a more mobile and deformable material moves upward through a less mobile solid or fluid one (such as is observed in a lava lamp). On Europa, diapirs of ice within the shell may be buoyant either because they are warmer (although composed of ice, they may still flow on geological timescales), or because they are compositionally less dense (as when salt diapirs rise up through rocks on Earth). As buoyant diapirs of ice move upward (e.g., Fig. 3), impurities are expected to segregate out efficiently and drain downward toward the ocean (ice being less dense than liquid water or brines), so the lower part of the shell is likely to be relatively clean. It is likely that buoyant diapirs move up through the ice shell but stall below the cold, stagnant outer lid, or they may be warm enough to melt material, such as frozen brines, within the shell, causing pockets of melt within the ice. It is thought that some diapirs may have been sufficiently buoyant to reach

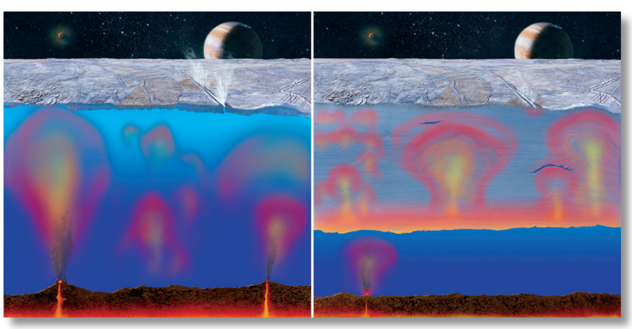

Figure 3. The thickness of Europa's ice shell has fundamental implications for the processes that occur within the shell as well as for Europa's habitability. On the left is an artist's depiction of an ice shell only a few kilometers thick above a deep liquid ocean. Here, the ocean has relatively easy access to the surface, and volcanic plumes from the ocean floor may directly affect the surface. On the right, the ice shell is a few tens of kilometers, sufficiently thick for the process of convection to occur. Here the ice shell is fairly uniform in thickness and diapirs of buoyant ice well up to form surface features. The total ice and ocean thickness in both cases is believed to be approximately 150 km. JEO would be able to address the fundamental issue of whether Europa's ice is thin or thick. (Image courtesy of NASA/JPL-Caltech.)

the surface, causing melting and disaggregation of the ice into so-called chaos regions (see *Geology*).

The style of Europa's surface geology appears to have changed over its visible history, from lateral tectonics, forming wide ribbon-like bands of ice on the surface, to more vertical tectonics in which the surface has been disrupted from below by upwelling diapirs, to blocks of ice embedded in a dark matrix material (see *Geology*). Such surface changes could result from a gradual thickening of the ice above the ocean: early thin ice would have pulled apart relatively easily, forming linear fractures and band-like morphologies such as those that are observed in older surface terrains. As the ocean gradually froze, the ice may have reached a critical thickness, which would have allowed for the onset of convection and the upwelling of plumes (Fig. 3). Such thickening of the ice would have implications for the exchange of material between the ice surface and the underlying liquid ocean. Understanding the structure of the ice, and the nature of any contaminants within it, is a primary goal of JEO. Subsurface sounding would enable us to determine the shell structure; radar sounding would allow us to determine whether the ice is warm or cold, whether it is clean or dirty, and whether it is thin and thermally conducting or thick and convecting.

Because of the presence of an ocean, Europa's shell is thought to be decoupled from the interior, and it may be moving slightly faster than the rocky mantle. There is some geological evidence that the shell has "slipped" forward over recent time relative to the interior (that is, it may not be tidally locked with one hemisphere facing Jupiter), although there is debate about how much of this "nonsynchronous rotation" there has been (e.g., see Geissler et al.[9]). The movement of the shell across the tidal bulge would cause considerable stresses in the shell and would fracture the surface in predictable patterns. JEO should be able to determine how much, if any, nonsynchronous rotation has occurred by comparing patterns of linear features on the surface to those expected if the shell were fixed with one face toward Jupiter.

Ice is expected to flow relatively quickly on geological timescales and is thought to adjust itself to a fairly uniform thickness within a few millions of years after it is perturbed. Therefore, if JEO is able to measure gravity anomalies within the ice, this might be evidence of cryovolcanically active areas or of upwelling or downwelling regions within the shell.

Europa's Composition and Chemistry

Surface materials on Europa record its history and evolution. Europa is believed to be differentiated into a metal core, silicate mantle, and water-ice surface layer approximately 150 km thick (further divided into an ice shell and liquid water ocean) (Fig. 2).[7] This differentiation likely mixed water with silicates and carbonaceous materials, resulting in chemical alteration and transport processes bringing material from the silicate mantle into the ocean, as well as material from the ocean up into the icy shell. Materials from the surface could be transported through the ice shell down into the ocean or sputtered by high-energy radiation and micrometeorites to form a tenuous atmosphere. The barrage of high-energy particles impacting the surface from Jupiter's magnetosphere (which acts like a giant particle accelerator) affects the chemical composition of material on the surface, clues to which are found in the tenuous atmosphere surrounding Europa. Identifying Europa's surface materials, and how they are affected by radiation, is key to understanding their origin and determining how the ocean interacts with the surface. This information would provide important constraints on our expectations of the habitability of Europa's ocean.

Europa's surface consists predominantly of water ice, along with hydrogen peroxide, sulfur dioxide, and carbon dioxide ices.[10] Additional surface compounds may have been created as the result of interactions with the interior and irradiation by charged particles.[11] These compounds take the form of dark, reddish material associated with fractures and heavily disrupted "chaos" regions on Europa's surface (Fig. 4). Data from the Galileo spacecraft's Near-Infrared Mapping Spectrometer (NIMS) instrument showed strongly asymmetric absorption features, indicating this material is highly hydrated (Fig. 4). There is disagreement about the chemical makeup of the dark materials; they have been suggested to be either sulfuric acid (common battery acid) or salty minerals, perhaps from a subsurface ocean (for a review, see Carlson et al.[12]).

JEO would resolve questions surrounding the compositions and origins of these hydrated materials by measuring their spectral signatures. On the basis of observations of other icy satellites, additional compounds are predicted to occur on Europa, and their presence or absence is important to understanding Europa's habitability. Photolysis and radiolysis alter pristine surface materials, forming highly oxidized species that react with other non-ice materials to produce a wide range of compounds. Complex organic molecules are unlikely to be found in older surface features because they have an increased radiation cross section and so are more susceptible to alteration by radiation. Despite the importance of the effects of exogenic (external source) processes on Europa's composition, much is still unknown about the chemistry and sources of implanted material. It is known that sulfur from Io is transported by the Jovian magnetosphere and is implanted into the ice on Europa, which may explain Europa's yellowish hue at global scales (e.g., Fig. 2). Once on the surface, this sulfur may create some of the dark materials by forming new molecules. Furthermore, variations are expected between Europa's leading and trailing hemispheres, because the Jovian magnetosphere rotates faster than Europa orbits Jupiter, thus high-energy particles impact or overtake Europa from behind (e.g., see Johnson et al.[13]). The trailing hemisphere is therefore expected to show different patterns of sulfur implantation and radiolytic chemistry. One important goal for JEO would be to separate the exogenic components of Europa's chemistry from those that result from endogenic (internal source) processes so that contributions from the interior can be properly evaluated.

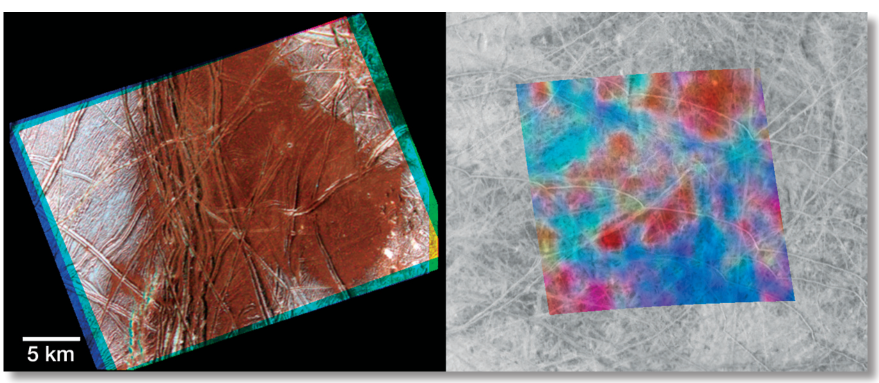

Figure 4. Evidence of dark, non-ice materials on the surface of Europa. (Left) Europa's Castalia Macula region is shown in this color (IR, green and violet) mosaic imaged by the Galileo spacecraft. This dark reddish region appears to be relatively young and may be an area where subsurface material such as brines have been brought to the surface. (Right) False-color image of Europa's surface, with data from Galileo's Near-Infrared Mapping Spectrometer (NIMS) instrument overlaid on the image. In this image, blue areas represent the cleanest, brightest icy surfaces, while the reddest areas have the highest concentrations of darker, non-ice materials. The area imaged in color is approximately 400 × 400 km (250 × 250 miles). (Image courtesy of NASA/JPL-Caltech.)

Geology

Europa's surface geology is varied and complex (for a review, see Greeley et al.[14]). The relative youth of the surface is inherently linked to the ocean and the effects of the gravitational tides, which trigger processes that include cracking of the ice shell, resurfacing, and possibly exchanging materials with the interior. Three major types of landforms exist on Europa's surface: linear fractures and ridges; chaotic terrain; and impact craters. Tectonic features at all scales dominate the surface of Europa and include simple troughs, double ridges separated by a trough (Fig. 5a), and intertwining ridge complexes. These ridges can measure more than 500 km long, are as wide as 2 km, and can be several hundred meters high. Cycloidal ridges are similar to double ridges but form chains of linked arcs.

Most models of linear feature formation include fracturing in response to processes within the ice shell.[14] Some models suggest that liquid ocean material or warm mobile subsurface ice squeezes through fractures to form a ridge, while others suggest that ridges form by frictional heating along the sides of a crack as it is worked back and forth by tidal processes. The arcs of cycloidal ridges can be well matched by models of cycling by Europa's diurnal tides, in which each arc forms during one orbit around Jupiter.[15]

Bands reflect areas where the surface has cracked and spread apart, allowing new material to well up from below into the gap (Figs. 5b and 5c), similar to seafloor spreading on Earth. Their surfaces vary from relatively smooth to heavily fractured, and they may be tens of kilometers wide and hundreds of kilometers long. Suggested models for their formation include those in which liquid water rises up from an ocean, freezes, then moves outward as the band is ratcheted apart,[16] and models in which warm ice rises buoyantly into the crack.[17] The latter model is favored by observations showing that bands stand tens to hundreds of meters above the surrounding terrain, but it would take topographic measurements and imaging by

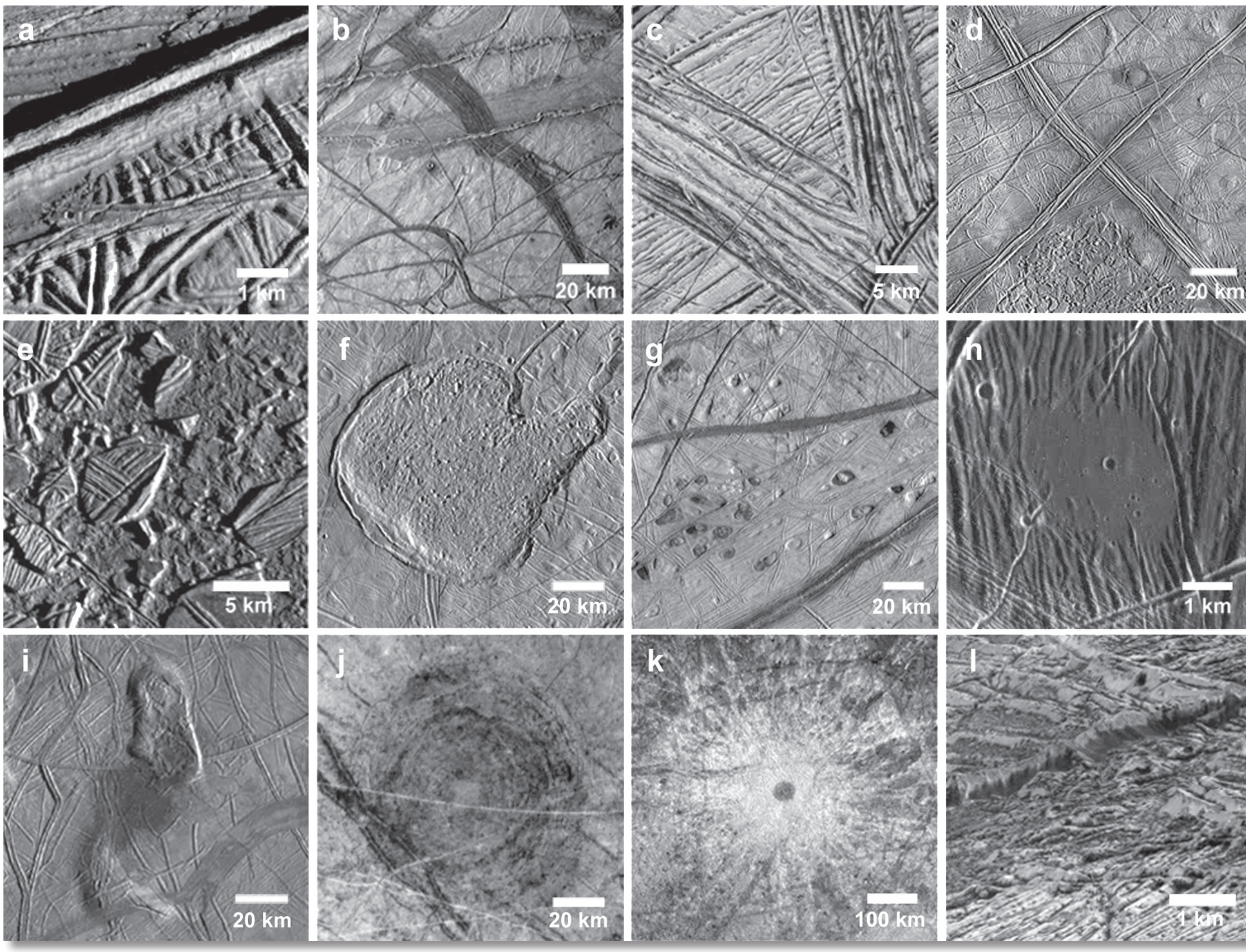

Figure 5. Europa is a geological wonderland, with a wide variety of surface features, many of which are unique to this moon. Although much was learned from Galileo, we still do not understand how many of these features form or what they tell us about Europa's evolution. Shown here are (a) one of Europa's ubiquitous ridges, at high resolution; (b) pull-apart bands, in which the surface has been completely pulled apart along a fracture, with new material filling the gap from below; (c) a pull-apart band at high resolution; (d) a regional view of two very large ridge complexes in the Conamara region; (e) Conamara Chaos, a region in which the surface has been cracked and disrupted by material moving upward from below; (f) Murias Chaos, a cryovolcanic (volcanic material where the lava is water or slushy ice) feature that appears to have flowed a short distance across the surface; (g) lenticulae; (h) dark plains material in a topographic low; (i) the Castalia Macula region, in which the northernmost dome contains chaos and is approximately 900 m high; (j) the Tyre impact feature, showing multiple rings; (k) the impact crater Pwyll, the youngest large crater on Europa; and (l) a very high-resolution image of a cliff, showing evidence of downward movement of loose material such as might happen in a landslide. (Images courtesy of NASA/JPL-Caltech.)

JEO to fully understand how these features form. It is anticipated that global mapping by JEO at regional resolutions (something that is currently not available) would allow the processes responsible for features observed in the ice bands to be determined.

Perhaps the most unusual morphological features on Europa's surface are regions where the surface has been disrupted to form what is known as chaotic terrain, or chaos. Chaos regions represent areas where the preexisting surface has broken up into plates, apparently sitting in a darker matrix of fine-textured material (Figs. 5e and 5f). Chaos regions may each cover thousands of square kilometers and in total represent 20–30% of Europa's surface. There are distinct variations in the morphology of chaos, ranging from areas with almost all matrix material to those with mainly large plates and little matrix. Smaller features, termed "lenticulae" (Fig. 5g; this term means "freckles" in Latin), appear to have a size range averaging approximately 15 km in diameter and may take the form of surface depressions or pits (Fig. 5f); domes, where the surface is uplifted and may be broken but not destroyed; and darker material, which appears to have a flatter surface and which has "embayed," or flooded the surrounding terrain (Fig. 5g). This dark material is sometimes observed near the margins of chaos terrain or as deposits on the surface that resemble frozen pools (Figs. 5h and 5i).

Several models have been proposed for chaos formation, but none of them completely describes the observations. One model proposes that chaos terrain results when the ice shell has directly melted over hydrothermal plumes within the ocean[18] (Fig. 3, left) and was proposed because chaos terrains resemble terrestrial icebergs. This model is attractive because it explains the characteristics of chaos. However, given our current understanding of tidal heating and ice properties, it is virtually impossible to focus enough heat in one area to melt through the ice shell. A second model is one in which chaos and lenticulae form above upwelling diapirs of buoyant ice, which move upward through the shell and get close enough to break apart the surface and form matrix material[19] (Fig. 3, right). This model, however, has difficulty explaining the size distribution of chaos regions, especially the smallest features. It seems likely that some kind of hybrid process is in effect in which diapirs could impinge on pockets of lower-melting-point brines (which would act like pockets of antifreeze) within the ice, producing smaller features that would explain the observations.[20]

The third type of landform found on Europa's surface is the scars of impacts. Very few craters larger than 20 km are observed, implying that Europa has been resurfaced recently and leading to estimates of the average surface age of approximately 60 Ma.[6] The topography and morphology of craters provide insight into the thickness of the ice layer when they formed. Craters up to 25 or 30 km in diameter have morphological characteristics consistent with formation in a shell that was warm, but solid, whereas the two largest impacts, the multiring Tyre (Fig. 5j) and Callanish, may have punched right through the brittle ice shell into a liquid ocean.[6,21] The youngest crater on the surface is thought to be the 24-km-diameter Pwyll (Fig. 5k), which preserves its bright rays and is thought to be less than 5 Ma.[22] JEO would carry out a global mapping survey of Europa, enabling impact features to be mapped at resolutions down to tens of meters and leading to a better understanding of the surface age and variations within it.

Europa's Habitability

Europa is believed to have a liquid water ocean trapped beneath a relatively thin ice shell, possibly a few to tens of kilometers thick. This coupled with the recent discovery of active microbial life in extremely inhospitable terrestrial environments—such as within ocean vents on Earth, under conditions of high radiation flux, and in concentrated brines—makes Europa a prime target in the search for life in the solar system. Although it is not possible to tell from existing information whether life existed or persists on Europa today, we can determine whether the conditions there are capable of supporting living organisms.

From our terrestrial experience, life depends on liquid water, a photo- or chemical-energy source, complex organics, and inorganic compounds. Europa appears to meet these requirements (e.g., see Marion et al.[23]). The ocean is thought to have persisted since the formation of the Jupiter system and is thought to have conditions of pressure, temperature, and composition that are likely to be within the constraints of known life on Earth. The ocean, lying as it does beneath kilometers of ice, is too deep to allow sunlight to penetrate and photosynthesis to occur; however, energy could be provided through radiolytic chemistry in which radiation causes dissociation of chemical bonds, releasing energy and creating new chemical products. Further energy could be supplied by tidal heating, which may be significant within Europa's ice shell, and perhaps hydrothermal energy from the rocky seafloor. The constant tidal squeezing of Europa promotes the exchange of surface and subsurface material, potentially cycling ocean material to the surface and vice versa. JEO would set constraints on our expectations of the habitability of Europa by investigating the structure of the ice shell and how material moves through it and understanding the magnitude and role of tidal heating and the chemical composition of the surface.

Europa's Atmosphere and Plasma Environment

Plasma swept up in Jupiter's rapidly rotating magnetosphere overtakes Europa and preferentially flows onto and weathers its trailing hemisphere. Energetic particles sputter neutral particles—many of these particles immediately return to the surface, but some become part of the satellite's tenuous atmosphere while others escape to space. Some fraction of the neutrals that are no longer bound to the moon form a circumplanetary neutral torus.[24] The dominant source of particles in Jupiter's magnetosphere is Io, although other moons contribute minor species and water.[13]

Europa's very tenuous atmosphere represents the interface between the moon's surface and Jupiter's magnetosphere, providing an important link to surface composition. Ion sputtering of Europa's surface is the principle means by which this atmosphere is maintained. The atmosphere is predominantly composed of O_2,[25] with a surface pressure of less than 100 billionth that of Earth's atmosphere at sea level. Hubble Space Telescope images have shown the atmosphere to be nonuniformly distributed for reasons that are not understood and that would be addressed by JEO. Once in the atmosphere, the molecules are subsequently ionized and dissociated by solar photons, electron impact, and charge exchange. Some atmospheric constituents such as sodium and potassium are more readily observed in their gas phase once liberated from the surface, and their abundance relative to that on Io provides a means to discriminate between exogenic and endogenic origins for these species.

Jupiter System

Before JEO enters orbit around Europa, it would spend 2.5 years in the Jupiter system, studying the other satellites, especially Io, as well as Jupiter's clouds and weather patterns, the Io torus (a donut-shaped ring of gas surrounding Jupiter), and Jupiter's rings and small satellites.

Despite being part of the same planetary family, the large moons of Jupiter show considerable variation in their surface geology and interior structure (Figs. 2 and 6). These differences can be attributed to their orbital evolutions, positions with respect to Jupiter and one another, and consequent tidal heating.

Io, being closest to Jupiter, is undergoing intense tidally driven volcanism and may harbor a magma ocean. It is the most volcanically active body in the solar system with a heat flux of approximately 2 W/m^2, which is 25 times greater than that of Earth's, and no observed impact craters. Io, Europa, and Ganymede are in a 4:2:1 Laplace resonance (meaning that Io orbits Jupiter four times for every two orbits of Europa and a single orbit of Ganymede). This resonance leads to tidal flexing of approximately 100 m at Io's surface, generating the heat that powers its global volcanism.[27] Europa's interior is probably very similar to Io's but with a water-ice layer on the surface (Europa has been described as "Io à la mode") (Fig. 2), so understanding Io's tidally driven heat engine

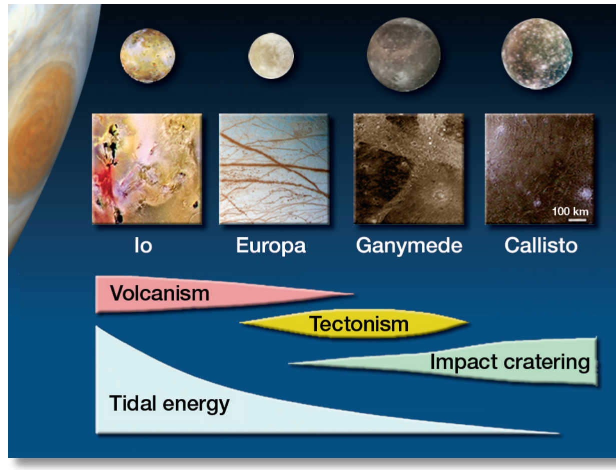

Figure 6. Both the level of geological activity and the degree of tidal heating of the Galilean satellites decrease significantly with distance from Jupiter. The satellites provide a natural laboratory for understanding processes that control the emergence of habitable worlds around gas giants. (Image adapted with permission from Ref. 26, © 2004 Cambridge University Press.)

and its effect on the interior will provide a window into Europa's silicate interior.

Many styles of volcanism are present on Io and range from short-lived, intense, fissure-fed eruptions associated with plumes to extensive pyroclastic deposits, lava lakes, and long-lived compound flows fed by lava tubes or sheets (Fig. 7).[28] Silicate volcanism dominates, although secondary sulfur volcanism may be important on local scales. Many volcanic plumes have been observed by spacecraft, including a spectacular eruption of Io's volcano Tvashtar that was imaged by the New Horizons spacecraft as it passed through the Jupiter system (Fig. 7). Changes in surface deposits have been documented since Voyager first returned images of Io's surface.

In addition to volcanism, approximately 2% of Io's surface contains vast mountains (Fig. 7), some more than 17 km high. These mountains are believed to have formed very quickly on geological time scales, when the lower part of the crust was compressed because of rapid burial by the constant eruption of volcanic material on the surface. To release the stress, the crust is thought to have pushed upward, forming the mountains.[28]

The third satellite from Jupiter is Ganymede, which is larger than the planet Mercury. Ganymede is remarkable in that it is one of only three bodies in the solar system with its own internally generated magnetic field (the other two are Earth and Mercury). Its field is 40–80 times smaller than Earth's yet is strong enough to generate a mini-magnetosphere that can stand off the Jovian magnetosphere.[29] The most plausible mechanism for the generation of Ganymede's magnetic field is dynamo action in a liquid iron core.[30]

Ganymede's interior appears to be differentiated into an outermost thick ice layer and an underlying silicate

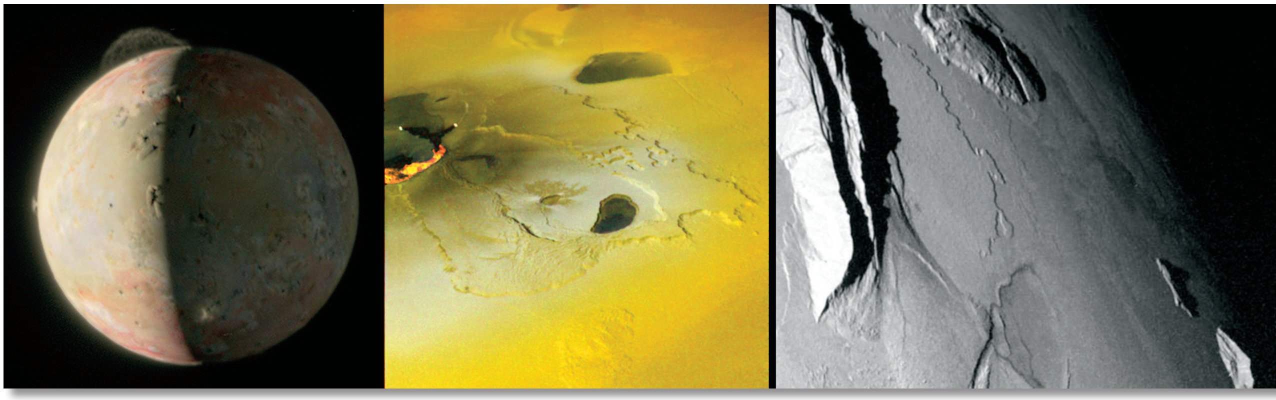

Figure 7. (Left) Two volcanic plumes on Io, as imaged by the Long Range Reconnaissance Imager (LORRI) instrument on the New Horizons spacecraft as it sped through the Jupiter system. A 290-km-high plume from the volcano Tvashtar (visible above the top surface of the moon) shows detailed structure. A smaller 60-km-high plume (left side of the moon) is visible from the volcano Prometheus. This plume has been active during all spacecraft flybys since Voyager. (Center) Surface view of the Tvashtar region as observed by the Galileo spacecraft showing active glowing volcanic flows (left side of image) and several volcanic calderas. Volcanism on Io is rocky, not icy as on Europa. (Right) Galileo image of mountains on Io taken when the sun was low in the sky and illuminated the scene from the left. The jagged ridge on the left side of the image is Mongibello Mons, which rises more than 7 km (4.3 miles) above the surrounding plains. This mountain is higher than Alaska's Mount McKinley, the tallest mountain in North America. (Images courtesy of NASA/JPL-Caltech.)

mantle[31] (Fig. 2). It may have a central iron core, an inference supported by the presence of Ganymede's magnetic field. Galileo magnetometer data have provided tentative evidence for an inductive response at Ganymede, which suggests the presence of a salty internal ocean, although unlike Europa, Ganymede's ocean is probably 100–200 km below the icy surface.[32]

About one-third of Ganymede's surface is composed of older, cratered dark terrain, and approximately two-thirds of its surface is composed of younger, brighter terrain that is heavily "tectonized," or cut by grooves and fractures.[33] This bright, or "grooved," terrain is arranged into linear swaths (Figs. 6 and 8). The older, dark terrain contains numerous impact features, including hemisphere-scale sets of concentric troughs termed furrows, which are probably remnants of vast multiring impact basins now broken up by subsequent bright terrain formation.

At some point in its evolution, Ganymede underwent a massive resurfacing event that did not go to completion. Its surface therefore appears caught in time between ancient, heavily cratered Callisto, and younger, i.e., less cratered, Europa. The grooved terrain was originally thought to result from tectonic troughs forming in the dark terrain that were later flooded by cleaner ice and perhaps further tectonized (e.g., see Pappalardo et al.[33]). Imaging by the Galileo spacecraft was unable to equivocally demonstrate that this process had taken place and, instead, it was proposed that grooved terrain was simply dark, older terrain that had been so heavily fractured that preexisting landforms such as craters were no longer visible. The origin of Ganymede's grooved terrain still presents a mystery that JEO would help solve, and by doing so, it would provide a greater understanding of Ganymede's orbital evolution and resonance states.

Of the four Galilean satellites, Callisto is the least affected by tidal heating and is the least differentiated (Figs. 2 and 6), offering an "endmember" example of satellite evolution for the Jovian system. Its internal structure appears to be only partially differentiated, with an ice-rich outer layer less than 500 km thick, an intermediate ice-rock mixture below, and possibly a central rock or iron core.[34] Galileo magnetometer data indicated that Callisto also has an inductive magnetic response best explained by a salty ocean within 200 km of the

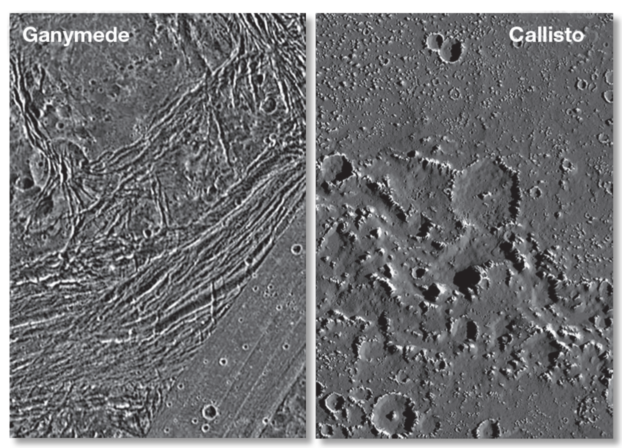

Figure 8. Comparison of the surfaces of Ganymede (left) and Callisto (right). Each image is approximately 70 km wide. Ganymede's surface is partially covered with swaths of heavily fractured terrain, some of which appear smooth, such as those shown in the bottom-right corner of this image. Callisto's surface is dominated by impact craters and basins and appears heavily eroded.

surface.[8,35,36] Reconciling the presence of an ocean with partial differentiation is difficult—some part of the uppermost ice layer must remain at the melting temperature, whereas the mixed ice-rock layer must never have attained the melting temperature. More data from Callisto will be key to solving this conundrum.

The major landforms on Callisto's surface are impact craters and large basins (Figs. 6 and 8),[37] some of which, like the 1500-km-diameter ring system of Valhalla, are vast and ancient. At higher resolutions, the surface appears to have undergone degradation through sublimation of volatiles (similar to the way a dirty snowball will eventually turn into a pile of dirt once the water evaporates) and exhibits a dearth of small craters, which may yield clues to the cratering process on the Galilean satellites. When studied together, the four largest Jovian moons clearly show the effect of tidal heating on surface activity (Fig. 6).

In addition to studying all four Galilean satellites before entering orbit around Europa, JEO would undertake a campaign to observe Jupiter's atmosphere. Jupiter's present-day atmospheric composition reflects a processed version of the initial nebular conditions from which the Galilean moons formed and evolved, so studying it is important to understanding the starting conditions of the moons.[38] Important questions exist about Jupiter's own visible upper atmosphere or "weather-layer," which contains dynamic and chemical processes likely governed by radiative forcing due to the deposition of solar energy and forcing due to deeper internal processes. JEO would monitor such processes as storms, cloud formation, convection, jet streams, lightning, and wave propagation over timescales of hours to months or more (Fig. 9).[40,41]

Jupiter's tenuous rings and small moons encircle Jupiter within Io's orbit.[42] Dust ring orbits are perturbed by Jupiter's magnetic field and by solar radiation pressure, and they may provide valuable information about Jupiter's plasma and magnetic field environment in a region too close to the giant planet to be directly investigated by a spacecraft. Dust from the rings could be a source of exogenic material for the Galilean satellites, and the entire ring system provides a dynamic laboratory for understanding the formation of the Jupiter system.

SCIENCE IMPLEMENTATION

Model Payload

The lack of a substantial atmosphere at Europa is beneficial to an orbital mission because atmospheric scattering and absorption are not an issue even at low orbital altitudes (≤100 km), and the lack of atmospheric drag improves orbit and positioning knowledge. Such a low altitude allows increased sensitivity of some instruments.

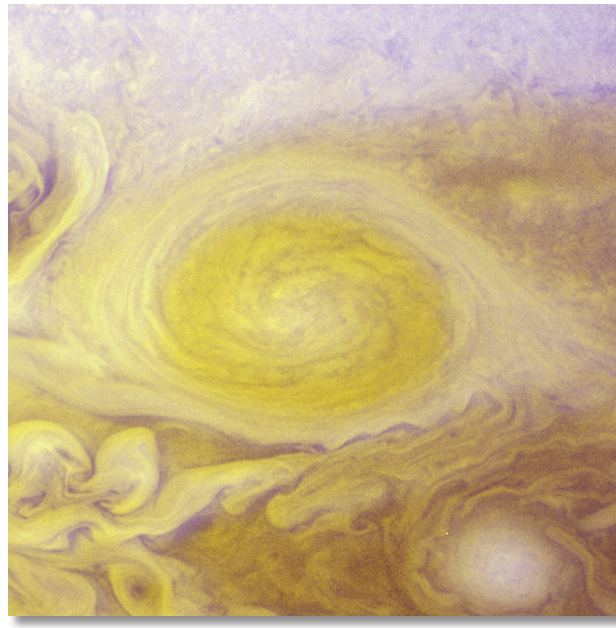

Figure 9. Image of Jupiter's Little Red Spot from New Horizon's Long Range Reconnaissance Imager (LORRI) instrument. The image has been colorized using images from the Hubble Space Telescope.[39] Image resolution is approximately 15 km/pixel. JEO would enable a better understanding of the development and dynamics of Jupiter's atmospheric storms. (Image courtesy of NASA/JPL-Caltech.)

The strawman payload proposed for JEO has been selected because of its ability to meet the detailed science requirements of the JEO mission determined by the Joint Jupiter Science Definition Team.[3] The payload is sufficient to test specific hypotheses and has the potential to make serendipitous discoveries. The most significant issue at Europa is the harsh radiation environment, which has significantly influenced the characteristics of the model payload and the spacecraft itself. Data acquisition strategies are also affected by the risk mitigations employed by the spacecraft, in that the highest-priority science objectives would be met as early as possible in the orbital phase.

The model payload comprises 11 instruments (listed below) plus radio science. The actual payload for JEO would ultimately be the result of an Announcement of Opportunity selection process, which would be carried out by NASA once sufficient funding for JEO has been secured. The model payload includes the following:

- Laser altimeter
- Ice-penetrating radar
- Visible-IR imaging spectrometer
- UV spectrometer
- Ion and neutral mass spectrometer
- Thermal instrument
- Narrow-angle camera

- Wide-angle camera
- Medium-angle camera
- Magnetometer
- Particle and plasma instrument
- Radio science

Mission Constraints

During the last several years the JEO project has worked with the engineering team and the science definition team to develop key science requirements and operational scenarios, and to define a proof of concept that, with the model payload, achieves all the primary science objectives. This is not to imply that JEO is devoid of technical challenges, most notably the severe radiation environment with a design dose of 2.9 Mrad (behind 100 mils of aluminum), planetary protection constraints, mission longevity, and desired operability. Significant efforts are being applied to better model the Jovian radiation environment, define the mission radiation design dose, and develop radiation risk mitigations. Together with JPL, NASA, and the science community, the project plans to employ a proven, disciplined engineering approach to maximize the science return from this flagship mission.

Science investigations for JEO place constraints on the mission design. Launched in 2020, Jupiter orbit insertion would occur almost 6 years later, and the spacecraft would spend the next 2.5 years in the Jovian system (Fig. 10), making multiple flybys of all four Galilean moons, monitoring activity on Io and Jupiter, and studying the rings, Io torus, Jovian magnetosphere, and smaller moons.

In 2028, JEO would enter Europa's orbit. The Europa orbital campaign is organized into four phases designed to accomplish the highest-priority science observations as early as possible because of the high radiation JEO will be exposed to. After a brief check-out period, data taking would begin with a global campaign at 200-km altitude. The altitude then would decrease to 100 km in order to focus on regional processes. Next, local-scale processes would be addressed, and the prime mission would finally end with a focused science campaign that would target follow-up observations on discoveries made earlier in the mission. This last campaign phase would also be used to characterize potential landing sites for future missions. The data acquisition strategy has been planned such that multiple instruments can simultaneously investigate the same part of the surface, enabling the maximum science return from the mission. Additionally, the spacecraft concept provides for concurrent science data collection and data transmission to Earth during the orbital phase. There is a strong desire to factor operability into the JEO design, as well as graceful degradation and fault management techniques to extend the mission's performance and science collection in this harsh environment. The Europa orbital phase of the mission is planned to last at least 9 months. After this time, once fuel is depleted (or systems degrade because of the radiation environment), the orbit will begin to decay. Ultimately the spacecraft will impact the surface of Europa, which means it must meet NASA Planetary Protection requirements that were established on the basis of recommendations set by the Committee on Space Research.[43] The Planetary Protection requirements mandate that the spacecraft meet extremely high standards of cleanliness so that there is virtually zero chance of any terrestrial organisms being transported to Europa and contaminating its ocean. The spacecraft and instruments would be designed to withstand the radiation in the Jovian system for no less than the complete tour phase plus the 9-month Europa orbital campaign.

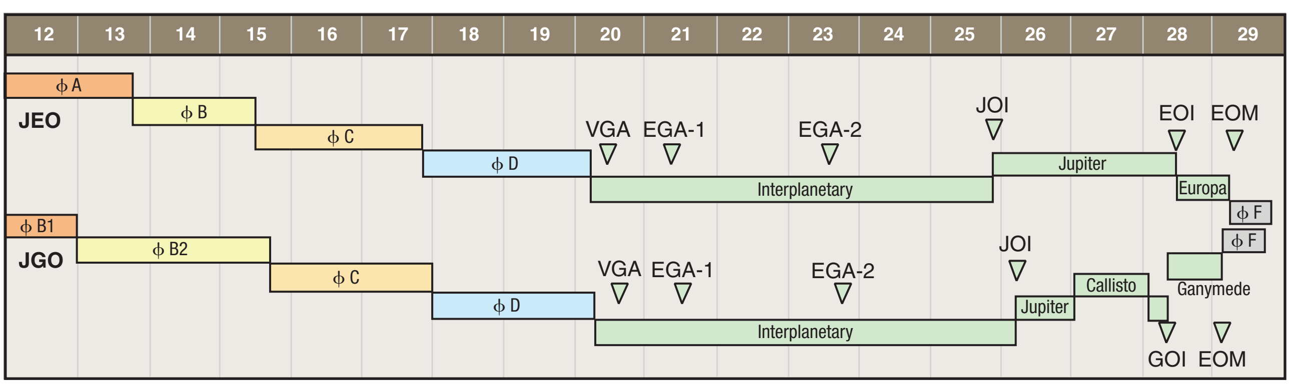

Figure 10. Proposed schedule of development for JEO and JGO, from the 2008 study report.[3] Both spacecraft would launch in 2020 and arrive in the Jupiter system approximately 6 years later. Both would spend approximately 2 years in the Jupiter system, offering ample opportunities for synergistic science. JGO would enter orbit around Ganymede in 2028, whereas JEO would enter orbit around Europa a few months later. ϕ, phase; EGA, Europa gravity assist; EOI, Europa orbit insertion; EOM, end of mission; GOI, Ganymede orbit insertion; JOI, Jupiter orbit insertion; VGA, Venus gravity assist. (Data courtesy of NASA/JPL-Caltech.)

Synergistic Science

Because ESA's JGO would be expected to launch at the same time as JEO and reach the Jupiter system at the same time (Fig. 10), there is the potential for unprecedented complementary and synergistic observations between the two spacecraft. Both spacecraft would make complementary measurements at similar or different times, but both would contribute to a greater picture of the whole. Synergistic science implies that measurements are made near-simultaneously, with dual measurements contributing more to the understanding of the system than could those made by one spacecraft alone. For example, two spacecraft could make simultaneous measurements of an Io plume from different vantage points, or one could measure how the solar wind impacts the Jovian magnetosphere from Io's orbit while the other spacecraft could make the same measurement from Ganymede's orbit. Such measurements would help to distinguish between temporal and spatial changes.

SUMMARY

The JEO baseline mission would provide a comprehensive study of Europa and meet almost all the goals of the 2003 National Academy of Sciences Planetary Decadal Survey.[2] In addition, the mission would return extensive data on the Jupiter system, hopefully in concert with a sister spacecraft from ESA, the JGO, which would allow groundbreaking synergistic science. APL has been a key partner in the study thus far and plans to continue to work with JPL to implement and fly a mission to Europa. In addition, APL would likely propose instruments for the payload.

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