Global color mosaic of Io produced from NASA's Voyager and Galileo missions. Simple cylindrical map projection. The large red ring is the plume deposit from Pele. IMAGE CREDIT: NASA/USGS.

Io: A Unique World in our Solar System

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Jupiter's moon Io is the most volcanically active world in our Solar System. Eruptions on Io sustain its atmosphere, feed the Jovian magnetosphere, and contaminate neighboring moons. This unique volcanic and tectonic activity is powered by tidal heating, caused by its gravitational interactions with Jupiter and other moons. The silicate crust of Io is coated with sulfur compounds, and its interior—one that is exceptional for an outer-planet moon—is composed of a metallic core and a silicate mantle that may host a magma ocean. Such spectacular large-scale volcanism and high heat flow provide insights into the processes that shaped all terrestrial bodies. Future exploration of Io would answer key questions and herald a new era of discoveries about the evolution of terrestrial planets and moons within our Solar System and beyond.

KEYWORDS: Io; Galilean satellites; tidal heating; interior structure; space exploration

INTRODUCTION

Jupiter's moon Io is one of the most intriguing celestial bodies in our Solar System. Its unparalleled physical and chemical properties are best described by superlatives. Io is predicted to have the highest solid tides in the Solar System, more than five times as high as the highest ocean tides on Earth, reaching up to 100 m in the case that Io has a "magma ocean" (i.e., a molten layer that detaches from the lithosphere). Tidal forcing originates from the gravity of Jupiter and the neighboring large moons, namely, Europa and Ganymede, causing the stretching and squeezing of Io. This symphony is perfectly orchestrated by the laws of physics. Io is less than 30% the size of Earth (1822 km versus 6378 km in radius), but the moon's surface hosts taller mountains, with summits that can reach up to 17.5 km above the plains, and its volcanoes are much more powerful than those on our planet today. Here, the most intense volcanism in the Solar System is observed, with hundreds of centers that are currently very active and constantly resurfacing the moon. This volcanic activity is also evidenced by Io's stunning colors, corresponding to sulfurous deposits (yellow, white, red, greenish), hot silicate lavas (bright red), cooled silicate lavas (dark grey), and scattering of small particles in active plumes (blue). Io has the greatest heat flow in the Solar System (>2 W·m^{-2}, which is >20 times Earth's heat flow), and most of its heat is expelled from paterae, volcanic depressions similar to calderas on Earth. Some of the biggest plumes observed in the Solar System are on Io, being up to 500 km high, and the longest active lava flows (400 km long) in the Solar System have been imaged on its surface. This exceptional volcanic activity sustains the presence of a thin atmosphere. Io also possesses the brightest (at extreme ultraviolet (UV) wavelengths) plasma torus in our Solar System, consisting of predominantly sulfur and oxygen ions and electrons distributed around the orbit of Io and forming a large ring-shaped cloud. The torus is a consequence of Io's volcanism as well as its proximity to Jupiter and its magnetic field.

Io is an ideal place to study processes important during the youth of terrestrial planets and moons, in our Solar System and beyond, after accretion and differentiation left them hot and partially molten, like Io is today. Io is a natural laboratory of young terrestrial bodies before cooling gave them their present-day structure and dynamics. Studying Io's heat and mass flow therefore provides an analog to young terrestrial planets and moons and, hence, a means to understand their evolutionary pathways.

This issue offers a journey to one of the most captivating worlds in our Solar System. There is a lot we know about Io, and even more that we do not. Several spacecraft flybys and many telescopic observations have revealed Io's fascinating and intriguing characteristics, and we are now reaching the limit of what existing observations can teach us. These observations have raised fundamental questions about Io's interior and evolution that only a space mission designed to study Io will be able to answer.

HISTORY OF IO DISCOVERIES

Io was discovered in 1610 using a newly invented telescope by Galileo Galilei (FIG. 1A). The same year, using independent telescope observations, Simon Marius also observed Jupiter's four giant moons and assigned them the names we use today: Io, Ganymede, Europa, and Callisto, all lovers of Zeus in Greek mythology. The discovery of these moons was fundamental to our understanding of the Solar System because it was the first time a moon was discovered orbiting a planet other than Earth, demonstrating that not all celestial bodies in the Solar System orbit the Earth (geocentric system), thus supporting the heliocentric model. Later Earth-based observations showed that, although it has a similar size and bulk density to our Moon, Io has different reflectance and thermal properties. However, it was not until the 1970s that the scientific exploration of Io took off

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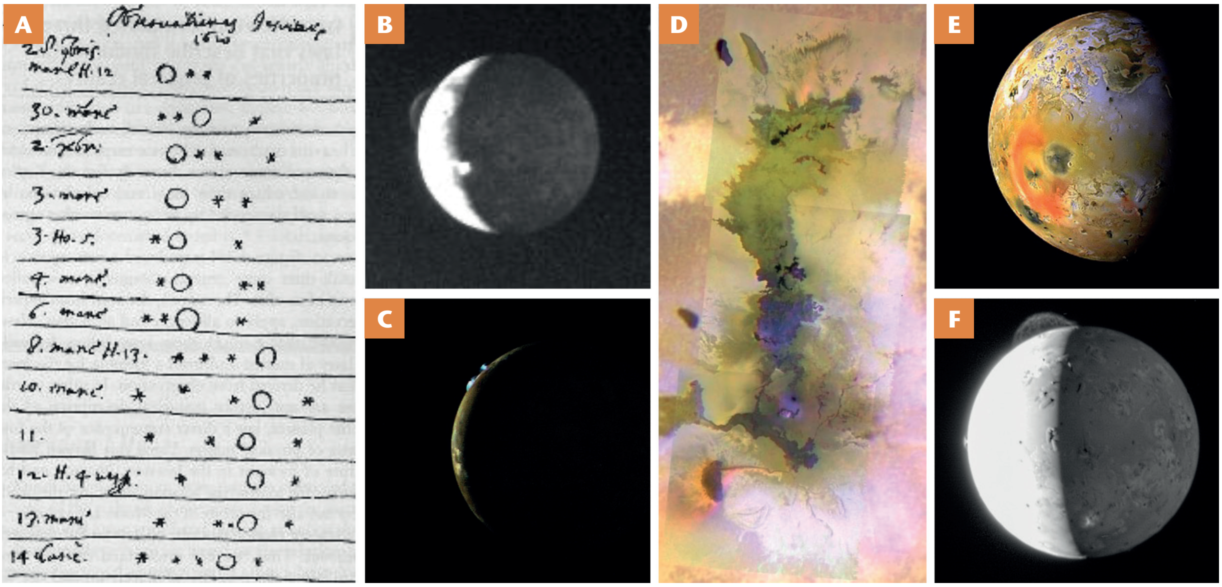

Figure 1 (**A**) Galileo's own notes of the changing positions of Jupiter's moons from night to night. (**B**) Historic photo of Io taken by *Voyager 1*. Pele's plume is on the left, and the Loki plumes are just beyond the terminator (day–night boundary). Photo: NASA JPL. (**C**) Photo from *Voyager 2* taken in 1979 showing the Amirani and Maui plumes. Photo: NASA/JPL. (**D**) Image mosaic of the Amirani–Maui region collected in February 2000 and the summer of 1999 by NASA's *Galileo* spacecraft showing the longest active lava flow known in the Solar System (extending for about 400 kilometers). Photo: NASA/JPL/University of Arizona. (**E**) Enhanced color view of Io as seen by the *Galileo* spacecraft in 1997, showing the red ring of Pele interrupted by the Pillan Patera plume deposits, an eruption with especially high temperatures. Photo: NASA/JPL/University of Arizona. (**F**) Image of Io's Tvashtar's plume (11 o'clock direction) by *New Horizons* in 2007. The Prometheus volcano in the 9 o'clock direction is also visible. Photo: NASA.

with the identification of large sodium clouds surrounding Io and several spacecraft observations. Approaching Io is particularly challenging because it requires surviving the intense radiation from Jupiter. *Pioneer 10* provided the first definitive evidence for an atmosphere around Io, with a surface pressure of 10^{-8}–10^{-9} bars (i.e., 8–9 orders of magnitude smaller than the pressure at the surface of the Earth; Kliore et al. 1974). *Pioneer 11* flew past Jupiter near Io's orbit in 1973–1974, showing that a spacecraft could survive, but collected only a single useful low-resolution image of Io along with important fields and particle data. Constraints on the atmospheric composition were established later (in 1979 and the following years) from *Voyager* and Earth-based telescopes, revealing that sodium, potassium, chlorine, sulfur, and oxygen species are abundant and feed the Jovian magnetosphere (e.g., Thomas et al. 2004; Bagenal and Dols 2020). In 1979, the *Voyager 1* spacecraft found a world covered with active volcanoes, much to the surprise of most scientists, although Peale et al. (1979) predicted extensive volcanism from tidal heating. The improved resolution of the images allowed the identification of volcanic caldera-like features called paterae, plumes (such as the more than 300-km-tall Pele plume; Fig. 1B), and lava flows. Although Peale et al. (1979) predicted a thin lithosphere over a molten interior, *Voyager 1* revealed many tall mountains consistent with a thick lithosphere. The idea of a magma ocean inside Io generally lost favor, until revived by *Galileo* magnetometer data analyses (Breuer et al. 2022 this issue). Further images confirming volcanic activity were sent by *Voyager 2* (Fig. 1C).

A wealth of new information about Io's surface and interior was provided by the *Galileo* spacecraft, which conducted multiple flybys of the moon between 1995 and 2003. In particular, *Galileo* was able to measure the temperature at Io's active vents (Fig. 1D and 1E), revealing high temperatures, perhaps hotter than any lava erupting on Earth today (McEwen et al. 1998). The post-*Voyager* interpretation of dominantly sulfur eruptions (consistent with Io's colorful surface) had to be revised: the volcanic activity is dominated by mafic silicate volcanism (Davies and Vorburger 2022 this issue). *Galileo* also observed that volcanic hot spots are abundant at all latitudes, consistent with a combination of asthenospheric (shallow-mantle) and deep-mantle tidal heating (see Breuer et al. 2022 this issue). In 1999, the polar Tvashtar lava fountains were discovered. This volcano is characterized by a plume that is up to ~400 km high (Fig. 1F; Davies and Vorburger 2022 this issue). All of the data collected contributed to revealing that Io's intense volcanic activity results in the rapid and extensive resurfacing of its surface. In addition, *Galileo*'s gravity measurements indicated the presence of a metallic core (comprising ~20% of Io's mass) and a silicate mantle. The spacecraft could not detect an intrinsic magnetic field in Io, but recorded magnetic field perturbations that could be caused by electric currents in Io's interior or the surrounding plasma (Kivelson et al. 2004). *Galileo* confirmed that Io's shape is close to hydrostatic equilibrium, in agreement with previous observations by *Voyager*. In 2000–2001, the *Galileo* and *Cassini* spacecraft joined forces to provide complementary observations of Io's volcanoes. As *Cassini* approached Jupiter, the *Galileo* dust instrument reported a 1000-fold increase in dust production, assumed to be caused by volcanic eruptions on Io (Krüger et al. 2003). *Cassini* started observing UV emissions from the Io torus in October 2000 and observed that gas production in the torus was increased by only a factor of approximately three while the dust production increased by three orders of magnitude. This difference in production remains a mystery. The plethora of thermal, compositional, and physical measurements, especially during the *Galileo* mission, allowed the development of models of Io's interior structure and provided estimates of the amount of partial melt in its interior (Keszthelyi et al. 2022 this issue).

Since 2003, *New Horizons*, *Juno*, and Earth-based telescopes have provided distant views of Io's active surface. The dramatic image of the Tvashtar volcano's plume by *New*

Horizons in 2007 provided a clear view of filamentary structures in the plume (Spencer et al. 2007). Instruments from the ongoing *Juno* mission have been listening to radio emissions triggered by the interaction of Io with Jupiter's magnetic field, observing the aurora in Jupiter's atmosphere excited by the million-amp currents induced at Io, and flying through the flux tube that couples Io to Jupiter (Martos et al. 2020; Moirano et al. 2021). On Earth, using the world's largest telescopes, astronomers can also probe some of the moon's volcanic activity, with more than 75 hot spots tracked from 2013 to 2018 (de Pater et al. 2021). Despite all these discoveries, many open questions remain regarding Io's interior and evolution (e.g., de Kleer et al. 2019). For example, how did Io (and the other Galilean satellites) form? What are the compositions of Io's crust, mantle, and core? How are Io's mountains formed? Where is the tidal energy dissipated? What are the mantle dynamics, and how much melt does the mantle have? Is Io's core fully molten, and does it generate an intrinsic magnetic field? Answering these questions requires a dedicated, modern mission to Io (Thomas 2021; Keane et al. 2022 this issue), whose importance has been recognized by NASA's three planetary Decadal Surveys. Such a mission would open a new era in our understanding of Io, and of other planets and moons that have a lot in common with Jupiter's fascinating moon.

ORIGIN AND COMPOSITION OF IO, AND COMPARISONS WITH OTHER GALILEAN SATELLITES

Formation and Bulk Composition

Formation models of the Galilean satellites are constrained by space observations of the moons. In particular, the common direction of rotation of the moons around Jupiter as well as the low eccentricity and inclination of their orbits are consistent with formation in a thin disk of gas and dust left over from the Sun's formation. It is thought that the four proto-moons were accreted within the disk surrounding a growing Jupiter, which formed from the same disk. This accretion mechanism is not uncommon: this is also how planets form around a star. However, the details of the growth mechanisms of the moons are still unclear and different scenarios have been proposed. The growth could occur rapidly (tens to thousands of years) if all building blocks are present in the disk (Lunine and Stevenson 1982), or it could take 100 ky or more if the material is supplied progressively to the disk (Canup and Ward 2002). The latter mechanism has been favored to explain the different levels of differentiation among the four moons. Io, Europa, and Ganymede are fully differentiated into metallic cores and silicate (+/- water and/or ice) mantles and crusts, whereas Callisto is thought to be only partially differentiated. This diversity results from how the satellites formed and might suggest that Callisto underwent a late accretion phase, forming after the other three moons. However, our knowledge of Callisto's interior is not known sufficiently well to rule out complete differentiation (e.g., Gao and Stevenson 2013).

The composition of the Galilean satellites is another key to understanding their formation. Their densities vary monotonically as a function of their orbital distance to Jupiter, in contrast to their masses. The Galilean satellites have a compositional gradient of decreasing density (and increasing water-ice content) from Io (3530 $kg \cdot m^{-3}$) to Europa (3010 $kg \cdot m^{-3}$) to Ganymede (1940 $kg \cdot m^{-3}$) to Callisto (1830 $kg \cdot m^{-3}$). This compositional gradient could have formed in different ways (e.g., Madeira et al. 2021 and references therein) (Fig. 2): (1) An intrinsic explanation suggests that Io and Europa were born water-ice depleted because they formed in the hot region of the gas and dust circum-Jovian disk, preventing or limiting ice formation or preservation closer to Jupiter. In this scenario, it is likely that Io and Europa would have formed much earlier than Ganymede and Callisto. (2) An extrinsic explanation proposes that Io and Europa formed from water-ice–rich materials that they (mostly) lost as a consequence of hydrodynamic escape, giant impacts, intense tidal heating, and intense thermal radiation from Jupiter. In both scenarios, the large water-ice contents in Ganymede and Callisto are consistent with formation in the cold part of the disk, where volatiles are stable. Europa has a relatively thin ice shell and Io lacks ice. Vapor loss driven by accretional heating is consistent with a gas-starved satellite formation model. This model can be tested by measuring the ratio of deuterium to hydrogen (D/H ratio) of potential Europan water plumes by NASA's *Europa Clipper*.

Models predict a strong radial migration of planetesimals and satellites by aerodynamic and tidal forces in

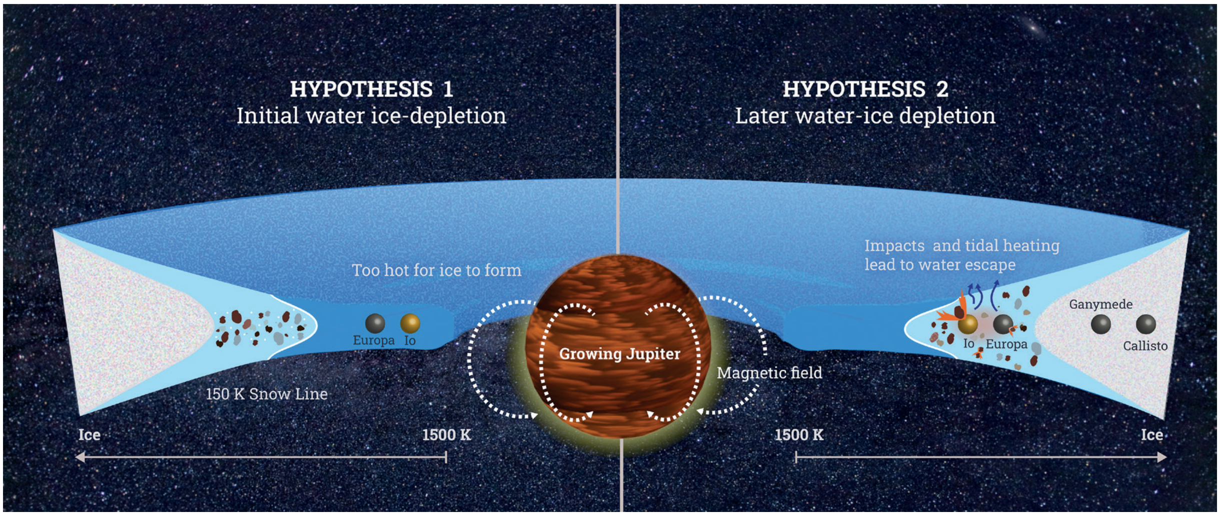

Figure 2 Possible scenarios for the formation of Io and the other Galilean satellites. (**Left**) Initial water-ice depletion hypothesis: Io (and Europa) formed close to Jupiter, where water ice is not stable. (**Right**) Later water-ice depletion hypothesis, in which Io (and Europa) accreted from water-bearing materials and subsequently lost their volatiles as a result of impacts and/or tidal heating. Image credit: Carnegie Institution for Science/Katy Cain and John Strom.

the circum-Jovian disk (Schubert et al. 2004). It has been argued that today's satellites are the final survivors of a history in which an earlier generation of satellites formed but were lost because they migrated into Jupiter. One idea to explain the compositional gradient is to invoke inward movement of the snow line in the final growth phases of the satellites. A formation scenario for the extrasolar TRAPPIST-1 system that has various ice mass fractions of planets may also apply to the Galilean satellites (Madeira et al. 2021). Thus, studies of the Galilean satellites and exoplanet systems are synergistic.

The Interiors of Io and the Other Galilean Satellites

Our knowledge of the present-day interior structure and composition of the Galilean moons is constrained by the Doppler data acquired by the *Galileo* spacecraft's radio communication system. These data have been used to determine the mean densities and moments of inertia (a quantity that characterizes the moon's resistance to angular acceleration) of the moons, allowing the development of interior models. Although the general features of the moons have been identified, especially using gravity measurements (Schubert et al. 2004 and references therein), their conversion to specific structures (e.g., radial profiles of density, temperature, composition) requires more data as well as careful modeling.

The interior of Io is explored by Breuer et al. (2022 this issue). The composition of Io is uncertain, but density profiles are consistent with a bulk composition of ordinary L and LL chondrites. Io contains a metallic core that is at least partly molten. Assuming a Fe–FeS composition, its size is thought to be ~950 km in radius, representing 20% of Io's mass. Io's mantle and thick lithosphere are made of silicates, and the amount as well as distribution of silicate melt is debated (Breuer et al. 2022 this issue). Estimates of tens of percent melt in the lava source regions have been suggested, and melt could be concentrated in the asthenosphere, characterized by a low viscosity, or be present throughout the entire mantle (de Kleer et al. 2019 and references therein) (Fig. 3). The presence and distribution of melt is tied to Io's volcanic and tectonic activity, as described in other chapters in this issue (Davies and Vorburger 2022 this issue; Keszthelyi et al. 2022 this issue). In comparison, Europa is also thought to have a metallic core and a rocky mantle, but a major difference with Io is the presence of a subsurface water layer, located within 200 km of the surface and as electrically conductive as seawater on Earth (Schubert et al. 2004 and references therein). Ganymede is differentiated into a water-ice shell, silicate mantle, and metallic core. *Galileo*'s magnetometer also found evidence of the presence of a magnetic field stronger than that of Mercury (Kivelson et al. 2004). The source of this field could be both an active core and a subsurface salty ocean. Like Europa and Ganymede, Callisto might possess a subsurface ocean. Its core is thought to be made of a mixture of ice and rock, rather than metallic iron.

IO–JUPITER INTERACTIONS

A distinctive trait of Io comes from its interactions with Jupiter. As the closest Galilean moon to Jupiter, Io's rotation is strongly locked to the planet and has been subject to the

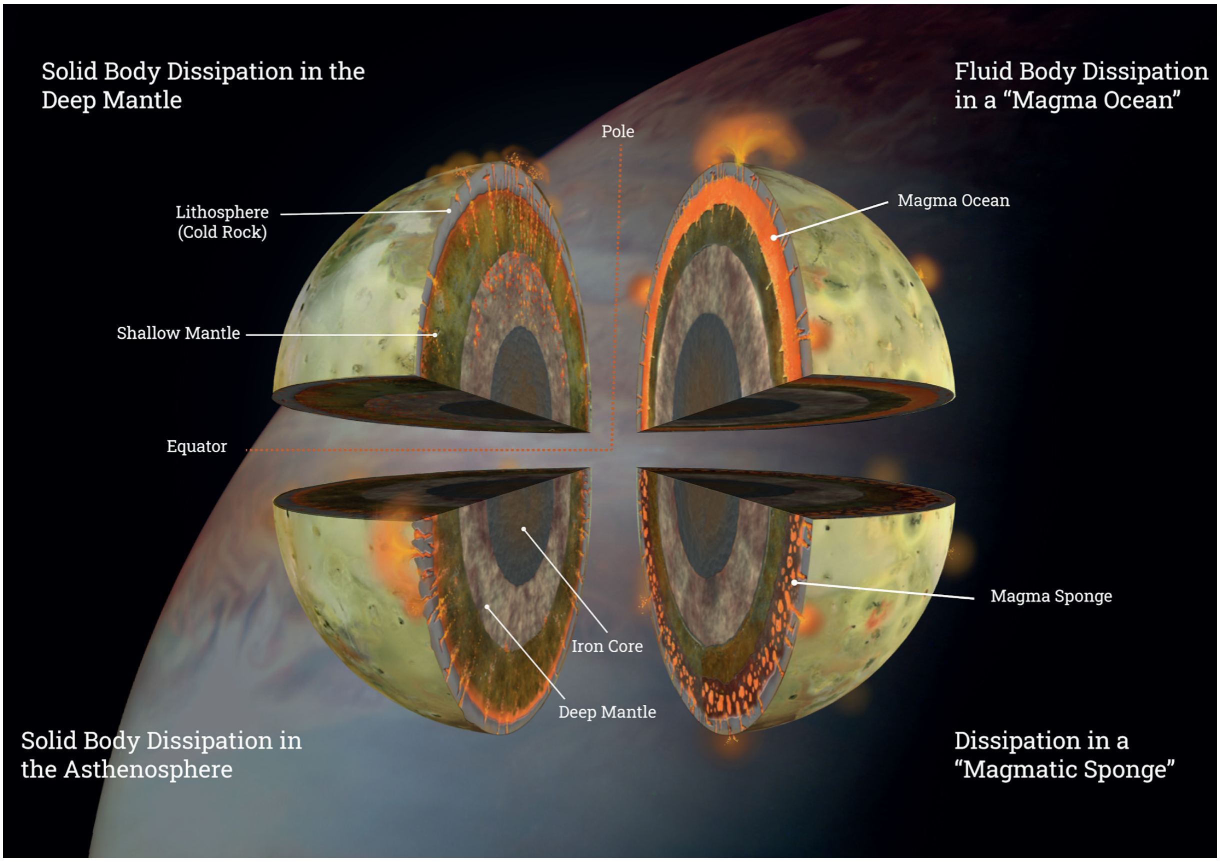

Figure 3 Interior structure of Io (after de Kleer et al. 2019). Different scenarios indicate different melt distributions. Credit for Io's surface: NASA. Image credit: Carnegie Institution for Science/Katy Cain and John Strom.

largest Jovian influence. In fact, Jupiter is responsible for many of Io's unique properties. Being a gigantic center of mass, Jupiter exerts gravitational forces that would have pushed Io's orbit outward except that it is counteracted by tidal dissipation, with orbital motions linked between Galilean satellites (especially Europa and Ganymede). Io, Europa, and Ganymede are in a first-order resonance (called a Laplace resonance), but Callisto is not (Matsuyama et al. 2022 this issue). Every time Ganymede orbits Jupiter, Europa orbits twice and Io four times, such that the moons periodically line up and pull on each other's orbits. This Laplace resonance results in an eccentric orbit of Io around Jupiter, in which the moon's shape periodically changes (Fig. 4). Without the neighboring moons, to which Io is resonantly locked, Io's eccentricity would disappear and so would the energy dissipation. The related energy dissipation is thought to be intense enough to trigger and sustain the volcanic activity on Io (Peale et al. 1979). Where exactly the tidal energy dissipates in Io's interior is debated: it could occur in the deep mantle, the upper mantle (asthenosphere), or both. Directly related to this question is the amount and distribution of melt in the mantle, and we still do not know whether Io possesses a magma-rich layer in its interior (Fig. 3). To address this question, new observations of Io are needed (Breuer et al. 2022 this issue).

Another remarkable interaction with Jupiter involves electromagnetism. Jupiter has a strong magnetic field that is intense at any location in Io's orbit. In contrast, our Moon encounters the magnetosphere of the Earth only once a month. Io loses a lot of matter to the magnetosphere of Jupiter (Davies and Vorburger 2022 this issue and references therein), forming extensive clouds of neutrals near Io. Some of these neutrals become ionized to form the Io plasma torus that corotates with Jupiter at Io's orbit. It has been estimated that Io loses about 1 ton of matter per second (Thomas et al. 2004). Neighboring bodies are directly impacted by Io's plasma torus; for example, the moon Amalthea's surface is coated by sulfur from the torus. When the fast rotation of Jupiter (spin period of about 10 h) drags its magnetic field through Io, it induces a large voltage difference across Io's equator. This difference in the electric potential energy drives an electrical current in Io, estimated to be more than a million amperes (Acuña et al. 1981). Although the discovery of the Io plasma torus (reviewed by Thomas et al. 2004) was pivotal to better describe the intense electrodynamic interactions between Io and Jupiter, there are still many unknowns and details that require further exploration (Bagenal and Dols 2020).

COMPARISON OF IO WITH OTHER ANCIENT AND CURRENT WORLDS

Io is unique in our Solar System, but the mantle, tectonic, and volcanic processes active on Io today may be good analogs for the ancient terrestrial planets. All of the terrestrial planets likely hosted early magma oceans, encompassing part, most, or all of their interiors. Over time, the magma oceans gradually cooled, forming hot mantles with abundant partial melt. These young mantles experienced higher heat flows than today, and erupted ultramafic lavas at very high temperatures, with volcanic heat pipes serving to remove most of the heat (Keszthelyi et al. 2022 this issue). Io is the best place we can visit to gain a better understanding of these processes. In particular, Jupiter's moon can help us gain knowledge about different key moments in our planet's history, because the Ionian crust represents an analog of the Earth's Hadean (>4 Gy old) crust, and because, even in just the past 500 My, Earth has seen extremely high eruption rates like those on Io today, often associated with mass extinctions or oceanic anoxia events (Claphem and Renne 2019).

Despite their different surface compositions, Io and the icy moons (such as Europa, Ganymede, and Callisto, but also Enceladus and Titan) have something fundamental in common: tidal heating. These moons are in non-circular orbits, periodically experiencing a change in their

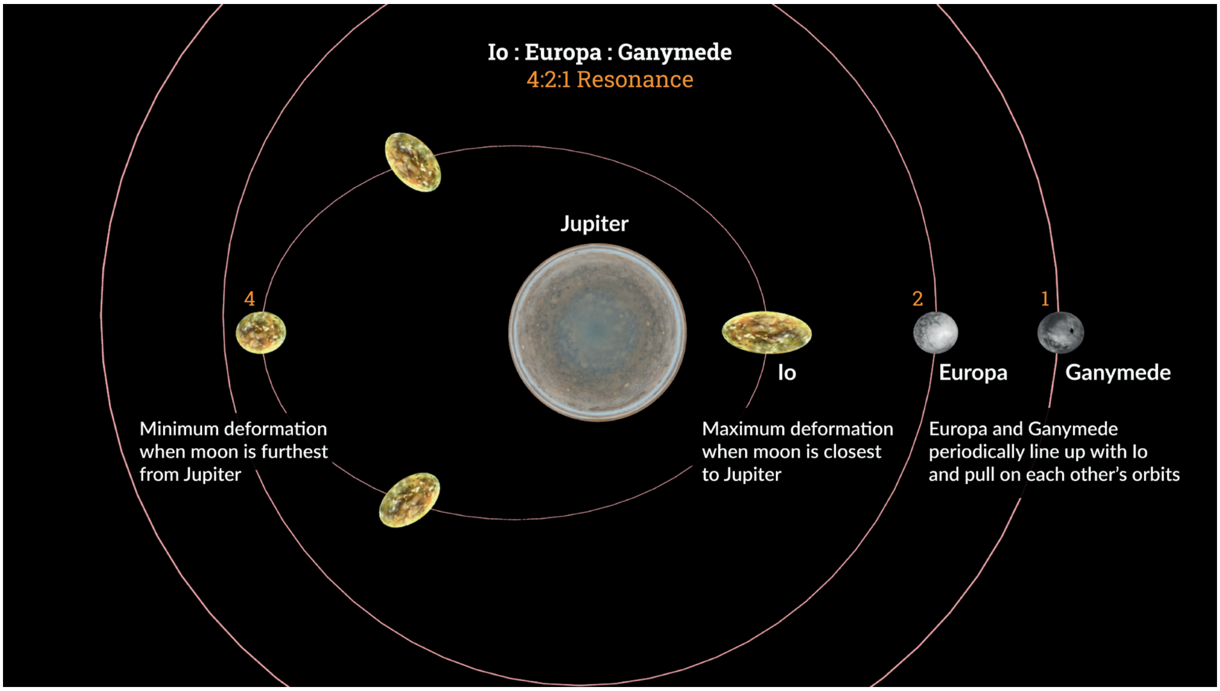

Figure 4 Tidal deformation of Io as it orbits Jupiter (view from Jupiter's north pole). Io is pulled and twisted back and forth along its orbit as a result of forces from Jupiter and its neighboring moons Europa and Ganymede (Io's shape and orbit are exaggerated here). Tides deform Io at all distances, and deformation is strongest when the moon is closest to Jupiter (pericenter) and weakest when it is furthest from Jupiter (apocenter). The numbers 4, 2, and 1 correspond to the orbital resonances of the three moons: when Io completes four orbits, Europa and Ganymede complete two and one, respectively. Credit for the planet and the moons' surface: NASA. Image credit: Carnegie Institution for Science/Katy Cain and John Strom.

gravitational attraction with the parent planet they orbit (planet–moon tides) and with their neighboring moons (moon–moon tides). The intensity of tidal forcing depends on the moon's interior composition and structure as well as its orbit. Tidal heating is less intense in these moons than in Io, but powerful enough to generate and sustain subsurface water oceans. Moons with a continuous liquid layer under their surfaces, such as a subsurface magma or water ocean, will be more sensitive to tidal forcing than moons without such a layer. Therefore, the tidal responses of moons can be used to probe their interior structures. As global fluid-rich layers, water and magma oceans display similarities, because the laws of physics that govern their dynamics at depth are identical. Understanding Io's tidally heated interior provides insights into the heat transfer and dynamics of icy satellites.

There may be abundant Io-like worlds around other stars or their giant planets, and Io is the best Solar System analog for understanding these exoplanets and exomoons (Barr et al. 2018; Rovira-Navarro et al. 2021). In particular, the TRAPPIST-1 exoplanetary system has seven planets orbiting close to its parent star, with tidal heating sufficient for magma oceans in several of these bodies. In fact, the surface heat flux estimates from tidal heating for two of the TRAPPIST-1 planets are comparable to that of Io (Barr et al. 2018). In addition, the orbital periods and eccentricities are similar to those of the Galilean satellites, and both systems have mean-motion resonances. Tidal heating could therefore keep many exoplanets and their moons warm in the galaxy, making the Galilean satellites and their interactions important analogs. These distant extrasolar worlds might be more diverse than the volcanically active worlds we know in our Solar System, in terms of chemistry, temperatures, volcanic styles, and orbital evolution. Another important point is that bright infrared fluxes and short orbital periods make volcanic exoplanets and exomoons with global magma oceans among the most detectable and characterizable low-mass exoplanets (Henning et al. 2018).

To summarize, there are many open questions about Io and tidal heating. Future exploration of Io has the potential to solve these mysteries and help us better understand many ancient and current worlds, in our Solar System and beyond (Keane et al. 2022 this issue).

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