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In This Issue

Planetary Environments, Part 8: Jupiter's Galilean Moons

by Garry Toth and Don Hillger (Un-manned Satellite Philately)

This is the eighth article in the *Astrofax* series on planetary environments. The first seven in the series appeared in the previous seven issues of *Astrofax*:
1. *Planetary Environments, Part 1: Introduction* (Volume 31, Issue 2, Summer 2023)
2. *Planetary Environments, Part 2: The Moon* (Volume 31, Issue 3, Fall 2023)
3. *Planetary Environments, Part 3: Mercury* (Volume 31, Issue 4, Winter 2023)
4. *Planetary Environments, Part 4: Venus* (Volume 32, Issue 1, Spring 2024)
5. *Planetary Environments, Part 5: Mars, Part 1* (Volume 32, Issue 2, Summer 2024)
6. *Planetary Environments, Part 6: Mars, Part 2* (Volume 32, Issue 3, Fall 2024)
7. *Planetary Environments, Part7: Jupiter* (Volume 32, Issue 4, Winter 2024)

This article is a continuation of Part 7 of the series. Ideally, the reader will be familiar with that article before reading this one.

Introduction

Xi Zezong, a historian of astronomy, has claimed that in 364 BCE the ancient Chinese astronomer Gan De visually observed "a small reddish star" that may have been Ganymede. Ignoring that, Galileo is generally credited with being the first to observe Jupiter's four principal moons in 1610 (Fig 1). They came to be known as the "Galilean Moons" and were the first moons discovered beyond Earth. This reference contains part of his original publication about them in the first edition of *Sidereus Nuncius*, from 13 March 1610. That they were celestial bodies circling an object other than Earth supported the Copernican view that Earth was not the center of the universe. They were the only known Jovian moons until Amalthea was discovered in 1892 by the American astronomer E. E. Barnard.

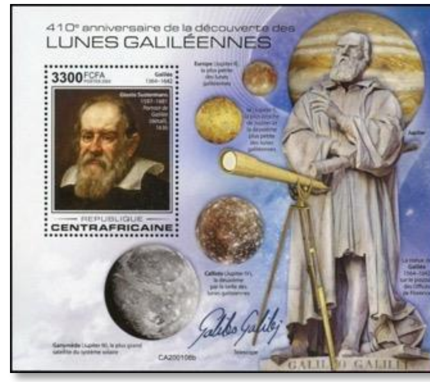

Figure 1. Central African Republic, BL2066, 2022

The German astronomer Simon Marius (Fig 2) observed the moons at around the same time as Galileo but is largely forgotten because he published his findings after Galileo. However, the names Marius proposed for the moons in 1614 (mythological characters associated with Jupiter, suggested to him by fellow astronomer Johannes Kepler) are the ones used today — Io, Europa, Ganymede and Callisto (listed in order of closest to farthest from Jupiter). This video and this reference discuss the four moons. There are many philatelic items that depict and identify them, such as the souvenir sheet of one stamp in Fig 1.

Figure 2. Germany, Marius meter, 2024

As we shall see, the three innermost moons exhibit some surprising characteristics that require a source of heat. What might it be? The answer is related to what is called "tidal heating." The Earthbound analogy is the oceanic tides, caused by changing gravitational forces as the Sun-Moon-Earth geometry changes. It turns out that such tidal forces can be large enough to change the shape of the *solid* parts of some celestial bodies, in an ongoing "tug-of-war" that generates friction, and therefore heat. The effect is particularly strong in moons that are in orbital resonance with other moons. Io, Europa and Ganymede are locked into a 4:2:1 three-body Laplace (Fig 3) resonance: for each single orbit of Ganymede, Europa makes two orbits and Io makes four. The resulting "inter-moon" tides generate

Figure 3. France, ScB298, 1955

significant heat inside those otherwise frigid bodies. Jupiter also contributes to this heating as its gravity works to maintain the moons' orbits against the deviations caused by the resonant effects.

A complicated pattern of ferocious radiation surrounds Jupiter in its magnetosphere. The three innermost Galilean moons are within that radiation zone while Callisto, farther out, avoids the worst of it.

Early spectroscopic observations by Earth-based telescopes showed that Europa, Ganymede and Callisto have significant ice cover. That was later confirmed by several spacecraft.

The trailblazing *Pioneer-10* & *-11* spacecraft were the first to fly through the Jovian system in 1973 and 1974. *Pioneer-10* provided new measurements of the masses of all four Galilean moons and estimated that each had an average daylight surface temperature of around -145 °C (Ref 1, pp. 88-89). In 1979, the *Voyager-1* & *-2* twin spacecraft provided more new information about the Galilean moons. In the 1995-2003 period, the Galileo Jupiter orbiter did multiple close flybys of all four of the moons and as we shall see made some significant discoveries. The *Juno* spacecraft (first named JUNO, for JUpiter Near-polar Orbiter), did a few flybys of the three inner Galilean moons in the early 2020s.

Io

"Telescopic observations in the mid-20th century hinted at Io's unusual nature. Spectroscopic observations suggested that its surface was devoid of water ice (a substance plentiful on the other Galilean satellites). The same observations suggested a surface dominated by evaporates composed of sodium salts and sulfur" (reference). *Pioneer-10's* encounter with the Jovian system is depicted in the event cover in Fig 4. Its cachet states that, among other goals, the mission was "to examine moons", and depicts the track of the spacecraft through the Jovian system. The three outer Galilean moons were on Jupiter's dayside while Io and *Pioneer-10* were on the nightside. The satellite was able to use radio occultation to show that Io has a surface-bound exosphere (reference) extending to about 115 km above its surface, and that the moon has an ionosphere extending to around 700 km above its dayside (Ref 1, pp. 88 and 90). An exosphere is an atmosphere so tenuous that its component atoms and molecules move without collisions.

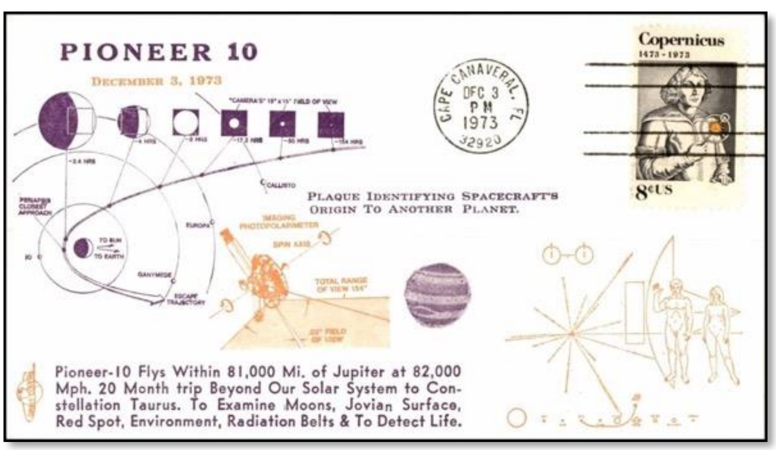

Figure 4. Pioneer-10 Event Cover, Jupiter Encounter, 1973

If it touches the surface, it is "surface-bound". Earlier articles in this series pointed out that Mercury and Earth's Moon have surface-bound exospheres.

The twin *Voyager* spacecraft flew through the Jovian system and observed Io in 1979 (the stamp of Fig 5 includes, in French text, "Volcanic eruptions on Io photographed by Voyager-2," though the depiction of Io, apparently under the "E" of "Eruptions," is so small as to be easily missed). Fig 6 has a much better depiction of the event: *Voyager-2* and Io are clearly defined in the margin of the SS1, with Jupiter in the background. The "discovery of active volcanism on the satellite Io was easily the greatest unexpected discovery at Jupiter. It was the first time that active volcanoes had been seen on another body in the solar system. The [two] Voyagers observed the eruption of nine volcanoes on Io … plumes from the volcanoes extended to more than 300 km above the surface. The Voyagers observed material ejected at velocities up to one km per second. Io's volcanoes are apparently due to heating of the satellite by tidal heating … [which] results in tidal bulging as great as 100 m on Io's surface … It appears that the volcanism on Io affects the entire Jovian system, in that it is the primary source of matter that pervades Jupiter's magnetosphere … sulfur, oxygen and sodium, apparently erupted by Io's many volcanoes and sputtered off the surface by the impact of high-energy particles, were detected as far away as the outer edge of the magnetosphere, millions of km from the planet itself" (Ref 2, p 4).

Figure 5. Burundi, Sc1262d, 2012

Figure 6. Guinea-Bissau, No cat#, 2024

Subsequent spacecraft refined those observations and confirmed that Io, whose intensity and frequency of eruption are reminiscent of early Earth, is the most geologically active body in the solar system, with volcanic activity possibly 100 times greater than that of Earth. The *Galileo* (in 1997) and *New Horizons* (in 2007) spacecraft photographed other volcanic eruptions on Io (images here). Fig 7 depicts Io and the astronomer Galileo. Fig 8 is inscribed "Galileo moving around Jupiter" in French text, but the celestial body is depicted with bright spots and contrasting colors and is clearly an artistic rendering of the extreme volcanism of Io, so this stamp can be considered to depict a *Galileo* flyby of Io. In the souvenir sheet of one stamp in

Figure 7. Liberia, No Cat#, 2024

Figure 8. Benin, Sc678, 1990

Fig 9, *Galileo* is depicted in the upper-left margin with its booster still attached, and in the stamp with its operational configuration. In both cases the satellite is just above a fiery surface with Jupiter in the background. This SS1 therefore also presents artistic depictions of one of *Galileo's* flybys of Io.

Figure 9. Malagasy, Sc996a, 1990

Galileo (in the early 2000s) and *Juno* (early 2020s) confirmed that material escaping from Io contributes to a belt of intense radiation known as the Io plasma torus that plays a major role in shaping Jupiter's magnetic field. "As the magnetosphere rotates with Jupiter, it sweeps past Io and strips away about 1000 kg of material per second. The material forms a torus, a doughnut-shaped cloud of ions that glow in the ultraviolet. The torus's heavy ions migrate outward and their pressure inflates the Jovian magnetosphere to more than twice its expected size. Some of the more energetic sulfur and oxygen ions fall along the magnetic field into the planet's atmosphere, resulting in auroras" (Ref 2, p 5).

The primary mission of *Juno* was to orbit and observe Jupiter, starting in 2016. However, in the early 2020s it did a few flybys of Io as part of a mission extension. Its JIRAM (Jovian InfraRed Auroral Mapper) observed a major hotspot that has been interpreted to be a large lava lake overlying a vast subsurface magma chamber system. Those observations strengthen the idea that there is "immense energy from frictional heating that melts portions of Io's interior, resulting in a seemingly endless series of lava plumes and ash venting into its atmosphere from the estimated 400 volcanoes that riddle its surface" (reference). A 3 February 2024 *Juno* image of Io is compared, here, with a *Galileo* image from 1997. Fig 10, the back of a Chinese postal card from 2002, depicts a volcanically active Io in the foreground and Jupiter in the background, along with a cartoon-style drawing of the Hubble Space Telescope (HST), which also made observations of the Galilean moons. The HST could "observe Io at UV wavelengths not seen by *Galileo*, observe Io at different times than *Galileo*, and view Io under more consistent viewing conditions" (reference). That web page also features an image of Io above Jupiter obtained by the HST on 24 July 1996.

Figure 10. China, Postalcard (back), 2002

Io has a surface-bound exosphere "consisting mainly [90%] of sulfur dioxide (SO_2), with minor constituents including sulfur monoxide (SO), sodium chloride (NaCl), and atomic sulfur and oxygen. The atmosphere has significant variations in density and temperature with time of day, latitude, volcanic activity, and surface frost abundance" (reference). Its average surface temperature is "about -130 °C, resulting in the formation of sulfur dioxide snowfields. But Io's volcanoes can reach 1649 °C. Io is often referred to as a celestial body of fire and ice" (reference). It also has an off-the-scale radiation environment: Io's "surface radiation level is 3600 rem per day — five times a lethal human dose. The radiation is strong enough to damage surface materials, darkening them, especially at Io's poles" (reference).

Europa

The two *Voyager* spacecraft provided a wealth of information about this moon. "Europa displayed a large number of intersecting linear features in the low-resolution photos from Voyager-1 … The closer high-resolution photos from Voyager-2 left scientists puzzled: the features were lacking in topographic relief." They hypothesized that Europa is internally active due to tidal heating and that it might have a liquid ocean beneath a thin crust of smooth water ice (Ref 2, p 4). Fig 11, a *Voyager-1* event cover, refers to the "thin ice surface."

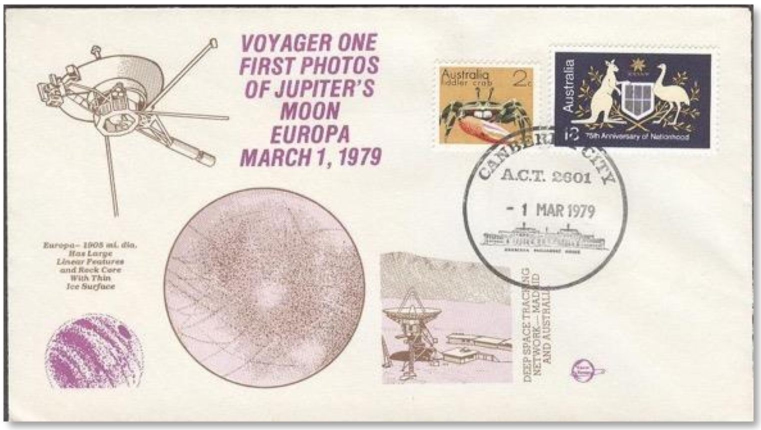

Figure 11. Voyager-1 Event cover, Europa, 1979

The HST "detected thin oxygen atmospheres (surface-bound exospheres) around Europa and Ganymede in the 1990s. On both Jovian moons, the oxygen comes from surface water ice, which splits into hydrogen and oxygen under heavy bombardment by charged particles from Jupiter" (reference). *Galileo* entered its Jupiter orbit in

Figure 12. Galileo Event Cover, 1996

Figure 13. Guinea, Mi10808, 2014

1995 and spent 8 years studying the planet and the Galilean moons. Fig 12 is an event cover for “E4,” the spacecraft’s fourth flyby of Europa, on 18 December 1996. It flew as close as 351 km above Europa on 3 January 2000. The stamp in Fig 13 depicts a *Galileo* flyby of Europa. The spacecraft found an anomaly in Jupiter’s magnetic field near the moon, which was consistent with the idea that Europa has an electrically conductive salty ocean beneath its ice layer. Then in the early 2010s, the HST observed possible water vapor plumes rising at least 160 km from the surface and found spectroscopic signatures of water vapor (reference). Hawaii’s Keck telescope also observed a probable water vapor plume later in that decade (reference). On 29 September 2022, during its perijove 45, *Juno* flew by Europa at a closest distance of 352 km and obtained images with resolutions as fine as 1 km per pixel. Fig 14 depicts a *Juno* flyby of Europa.

Figure 14. Liberia, No #, 2024

Ref 3 (pp. 130-131) provides a nice synthesis of our knowledge of Europa. Tidal heating, while not as great as in Io, still provides enough energy for a subsurface liquid ocean, thought to be between 60 and 150 km deep (while the icy shell may be 15 to 25 km thick). Earth’s seafloor has some hot hydrothermal vents (Ref. 3, pp. 123-128) that support life powered by chemical rather than solar energy. Ref. 3 also discusses Earthly life in cooler dark conditions inside pingos and deep caves. Could something like one of those processes exist on Europa? “Scientists say that there also could be large pockets of melted water in Europa’s ice shell, which are more likely than the ocean to be the source of plumes. These pockets could produce cozy habitats for organisms as well” (reference). “Flying as close as 26 km above the moon’s surface”, *Europa Clipper*, launched in October 2024 (Fig 15), “will use ice-penetrating radar and other sensors to seek out signs of liquid water within Europa’s ice shell and study organic molecules on its surface” (Ref. 3, p 130). The spacecraft’s elliptical orbit will allow it to do flybys of other Galilean moons as well.

Figure 15. Europa Clipper launch cover, GSC Cachet, 2024

Europa's surface temperature is around -160 °C at its equator and -220 °C at its poles. This keeps its frozen water crust as hard as rock. "The ionizing radiation level at Europa's surface is equivalent to a daily dose of about 5.4 Sv (540 rem), an amount that would cause severe illness or death in human beings exposed for a single Earth day (24 hours)" (reference).

Ganymede

The two *Voyager* spacecraft proved that Ganymede is the largest moon in the solar system, and that "it showed two distinct types of terrain – cratered and grooved – suggesting to scientists that Ganymede's entire icy crust has been under tension from global tectonic processes (Ref. 2, p 5). The *Voyager-2* event cover of Fig 16 illustrates this idea.

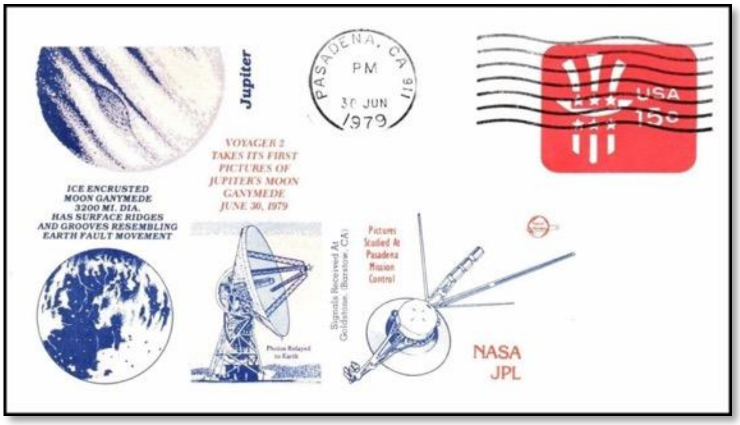

Figure 16. Voyager-2 Event Cover, SV Cachet, 1979.

In 1995, the HST found evidence for Ganymede's surface-bound exosphere. It "contains traces of oxygen, probably the result of ice on the surface broken down into molecular hydrogen and oxygen. Hydrogen has a lower escape velocity, leaving the traces of oxygen behind. There are also traces of ozone" (reference). Then in 1998, the HST captured the first UV images of Ganymede, which included auroras, from which it was deduced that the moon might have its own magnetic field.

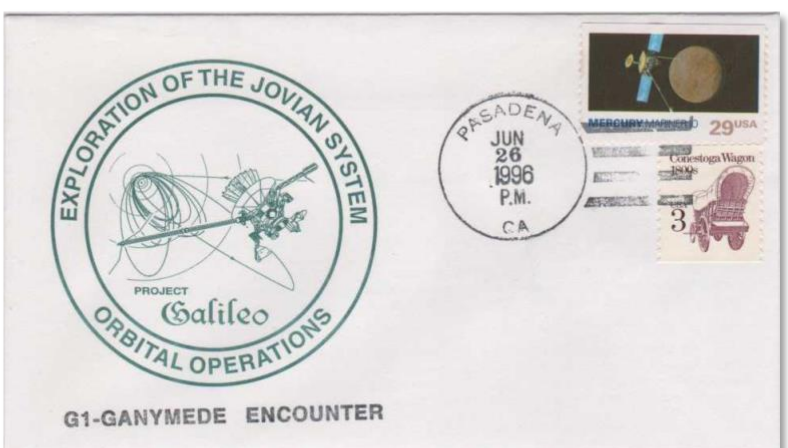

Figure 17. Galileo Event Cover, 1996.

Galileo made 6 close flybys of Ganymede from 1995 to 2000 (Fig 17 is an event cover for "G1", the first of them, on 26 June 1996) and confirmed that the moon has its own permanent magnetic field, independent of the Jovian magnetic field. "The permanent magnetic moment carves [out] a part of space around Ganymede, creating a tiny magnetosphere embedded inside that of Jupiter" (reference). This was a major discovery—no other moon in the solar system has such a feature. Combining this result with the fact that Ganymede undergoes some tidal heating, scientists concluded that it probably has a large salty liquid ocean below its icy surface. It might be 100 km deep under an icy crust 150 km thick, but the details are uncertain.

Galileo sent back "stunning close-up images showing ancient cratered ice fields adjacent to or overlain by younger ice volcanic plains, ridged ice mountains, deep furrows, and smooth broad basins that are products of tectonic forces" (reference), thus confirming interpretations that had been drawn from *Voyager* data. *Galileo's* near-IR spectra showed that the composition of Ganymede's surface "is dominated by a mixture of water ice, trapped carbon dioxide and other species" (reference).

In June 2021, just prior to its 34th perijove, *Juno* flew to within 1038 km of the surface of Ganymede (the closest approach since *Galileo's* penultimate close flyby on 20 May 2000) to study the moon's ionosphere, magnetosphere and radiation environment. It also used its MWR (Microwave Radiometer) to scan Ganymede's water-ice crust to obtain data on its composition and temperature. *Juno* Principal Investigator Scott Bolton of the Southwest Research Institute in San Antonio said that the "MWR will provide the first in-depth investigation of how the composition and structure of the ice varies with depth, leading to a better understanding of how the ice shell forms and the ongoing processes that resurface the ice over time" (reference).

ESA's *JUICE* spacecraft, launched in April 2023 (Fig 18), is "*en route* to perform two flybys of Europa as well as conduct in-depth studies of Europa's fellow Galilean moons Ganymede and Callisto, eventually entering into orbit around Ganymede (reference). "NASA's Europa Clipper … will conduct four close flybys of Ganymede beginning in 2030. It may also crash into Ganymede at the end of its mission to aid JUICE in studying the surface's geochemistry" (reference). Both will carry ice-penetrating radars: REASON (Radar for Europa Assessment and Sounding: Ocean to Near-surface) aboard *Europa Clipper*, and RIME (Radar for Icy Moon Exploration) aboard *JUICE*.

Figure 18. JUICE Launch Cover, Lollini Cachet, 2023

Ganymede's daytime surface temperatures range from around -123 °C at noon at the equator to -193 °C at night (reference). "The radiation level at the surface of Ganymede is considerably lower than on Europa, being 50–80 mSv (5–8 rem) per day, an amount that would cause severe illness or death in humans exposed for two months" (reference).

Callisto

The twin *Voyager* spacecraft provided the first detailed information about Callisto in 1979. It "has a very old, heavily cratered crust showing remnant rings of enormous impact craters. [Some of] the largest craters have apparently been erased by the flow of the icy crust over geologic time. Almost no topographic relief is apparent in the ghost remnants of the immense impact basins, identifiable only by their light color and the surrounding subdued rings of concentric ridges" (Ref 2, p 5, and Fig 19). Fig 5 depicts Callisto with the French text "Callisto photographed from a distance of 1 million km." Since *Voyager-2* is mentioned elsewhere in the stamp, one could infer that its Callisto image is also from *Voyager-2*. However, the only relevant photograph of Callisto found by the authors, here, was taken by *Voyager-2* from 2.3 million km. Callisto in that image is similar to the moon in the stamp, though.

Figure 19. Voyager-2 Event Cover, SV Cachet, 1979

Galileo did several flybys of Callisto in the 1996-2001 period. It carried the SSI (Solid State Imager) that had several science goals, including to "identify and map the distribution of ices and minerals on the various satellite [i.e. moon] surfaces" (reference). The SSI is illustrated in this web page, and the stamp of Fig 20 depicts it and the astronomer Galileo along with Callisto, thus implicitly referring to a flyby of the moon by the *Galileo* spacecraft. Fig 21 is an event cover for "C3", Galileo's third flyby of Callisto on 4 November 1996. Galileo came as close as 138 km above the moon's surface during its last Callisto flyby in 2001. Its observations confirmed that it has a dark surface composed of a mix of ice and rock and is covered with craters. "Callisto's rocky, icy surface is the oldest and most heavily cratered in our solar system. The surface is about 4 billion years old and it's been pummeled, likely by comets

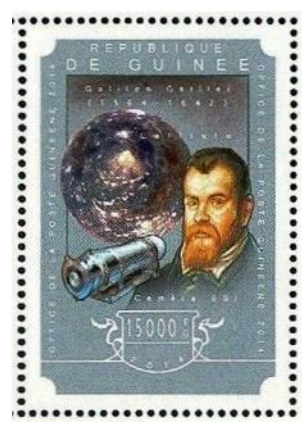

Figure 20. Guinea, Mi10810, 2014

and asteroids. Because the impact craters are still visible, scientists think the moon has little geologic activity -- there are no active volcanoes or tectonic shifting to erode the craters. Callisto looks like it's sprinkled with bright white dots that scientists think are the peaks of the craters capped with water ice" (reference). An alternate explanation is that "the bright spots peppering the surface are meteorite craters which have excavated through the dark surface and exposed the lighter material below" (reference).

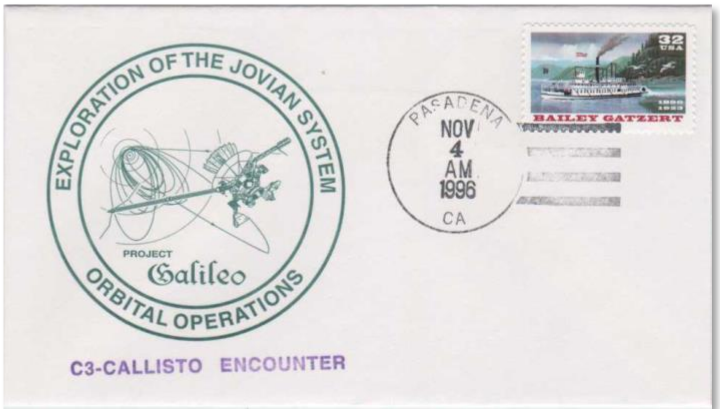

Figure 21. Galileo Event Cover, 1996.

From measurements made in 1997, *Galileo* detected Callisto's surface-bound exosphere, composed mostly of CO_2. More recent research found small amounts of oxygen and hydrogen as well.

Galileo also found that "Callisto responds to Jupiter's varying background magnetic field like a perfectly conducting sphere; that is, the field cannot penetrate inside Callisto, suggesting a layer of highly conductive fluid within it with a thickness of at least 10 km" (reference). The crust might be around 100 km thick. However, Callisto is unlike Europa and Ganymede in that it has little or no tidal heating to create such a liquid ocean, which may or may not exist. Beginning in 2030 and 2031, *JUICE* and *Europa Clipper* will "gather more data, some of it from very close to Callisto's surface. The *Europa Clipper* is scheduled to make nine flybys of Callisto. Seven will be within 1800 km of the surface, and four of those will be within 250 km. Its magnetometer will operate continuously during those flybys. The ESA's *JUICE* mission is scheduled to perform 21 flybys of Callisto. All of them will be within 7000 km of the surface, and most will be below 1000 km" (reference).

"In 2018, examinations of archival images taken by the HST in 2007 showed Callisto's effect on auroral bursts in Jupiter's atmosphere" (reference). Jupiter generates auroras on its own, but certain interactions with the Galilean moons can create Jovian auroral bursts. Callisto's effect is the weakest and was the last to be found. Callisto is located just outside Jupiter's main radiation belt. "The radiation level at its surface is equivalent to a dose of about 0.01 rem (0.1 mSv) per day, which is just over ten times higher than Earth's average background radiation, but less than in low Earth orbit or on Mars" (reference). Because of these relatively low levels, this moon would be the best choice for human explorers if they ever ventured to the Jovian system. Callisto's warmest surface temperature is around -108 °C in the daytime at the equator, while on the nightside it can drop to -193 °C (reference).

One possible mission design for the planned Chinese *Tianwen-4* spacecraft would send it into orbit around Callisto in 2035, with a lander that would go to the moon's surface. In another possibility, the spacecraft would conduct an in-depth study of Io (reference). This brings us full circle, since *Tianwen-4* was formerly named Gan De after the ancient Chinese astronomer referred to in the beginning of this article.

Other References

Ref. 1 Fimmel, Richard O. et al, 1974: Pioneer Odyssey: Encounter with a Giant. *NASA Scientific and Technical Information Division Report SP-349*, 171 pages.

Ref. 2 JPL Public Information Office, 1993: Voyager Outer-Planet Grand Tour. *NASA Fact Sheet 6-93*, 12 pages.

Ref. 3 The Alien Moonshot. *National Geographic* (Space Issue), October 2023, pp. 112-139.

Extensive lists of stamps and covers for the spacecraft discussed above (and many more) are found in the Planetary Spacecraft page of the authors' Un-manned Spacecraft website. Our list of philatelic items for Planetary Environments is also available online.

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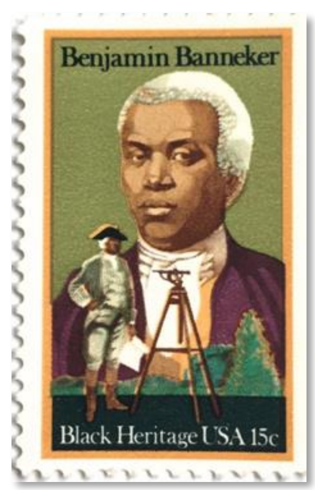
Benjamin Banneker: Pioneering African-American Astronomer

by Gene R. Major



On 15 February 1980, the USPS issued a 15¢ stamp (Sc 1804) commemorating Benjamin Banneker as part of its Black Heritage series. The stamp was designed by Jerry Pinkney and issued in sheets of fifty. This was the second stamp to be printed privately under the terms of a contract awarded by the Postal Service in 1978. It was printed by American Bank Note Company and J.W. Fergusson and Sons. Who was Benjamin Banneker?