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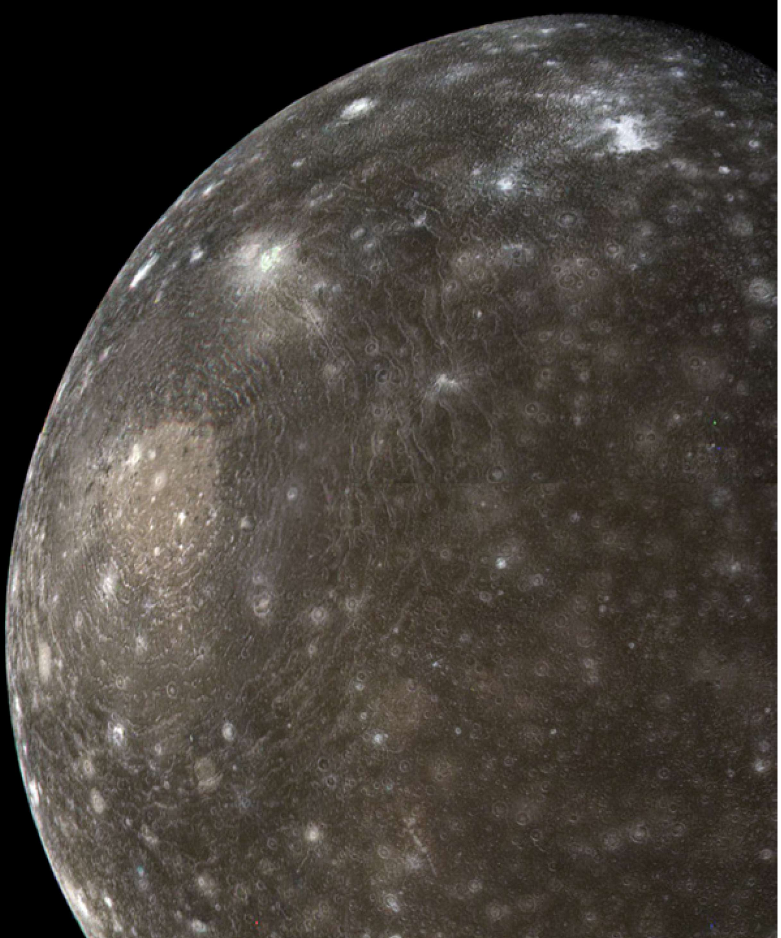
Moons



Uncovering the nature of three Jovian satellites took some curious twists and turns.

You may remember a scene from *Harry Potter and the Order of the Phoenix* in which Harry's know-it-all friend Hermione is correcting his astronomy homework at Hogwart's. She wryly informs him that one of his answers is *almost* correct: "Europa is covered in *ice*, not mice." Jupiter's moon Europa is indeed covered in ice, but its interior is only about 10% ice — the rest is rock and iron. Ganymede and Callisto have less ice on their surfaces, but more underneath. Volcanic Io, on the other hand, isn't an icy place at all.

So, how did astronomers figure this out? Long before the Space Age began, two key indicators suggested that Europa, Callisto, and Ganymede should be icy: their densities and their albedos.

Getting to the Basics

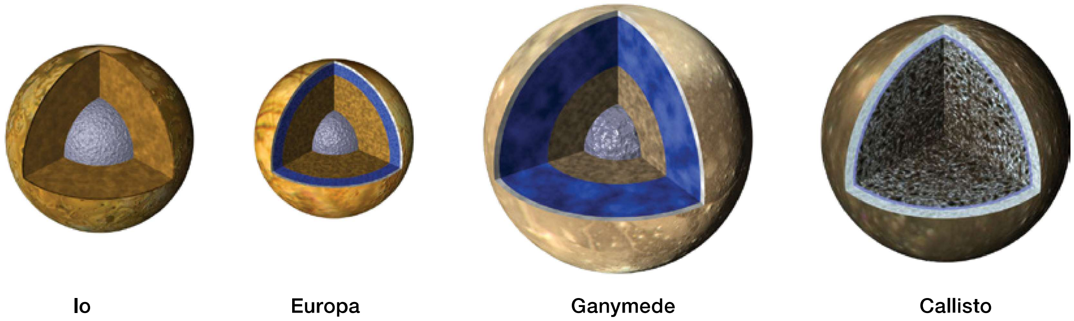
Assigning values to these indicators is where the real work lies. *Density* is simply an object's mass divided by its volume. For example, a cubic centimeter of iron weighs nearly 8 grams (0.3 ounces) and a cubic centimeter of ice weighs less than 1 gram. *Albedo* is the intrinsic reflectivity of a surface. Icy surfaces have especially high albedos — think of how blindingly bright a snowy landscape can be on a sunny day. But how do we measure the density and albedo of a distant body? The task isn't as straightforward as you might expect.

To get a handle on the first indicator, density, we first need to know the mass of a planet's moon, a task that can be very difficult. However, if more than one moon is orbiting the planet, then you can observe how each moon pulls on the others and work out the mass of each one. Doing so is a complicated calculation, but French polymath Pierre Simon Laplace accomplished it in 1805. Laplace was able to determine the masses of the Galilean satellites to within 10% to 25% of their currently accepted values.

To determine density, we need mass *and* volume. Unfortunately, you can't easily measure the width of a Jovian moon and plug that into the volume formula for a sphere. The moons appear as mere dots of light in small telescopes, and, due to diffraction effects, their apparent widths don't necessarily correspond to their actual sizes. However, that didn't stop 19th-century astronomers from trying. They employed filar micrometers with ultra-thin wires to measure the sizes of those dots, thinking they could do so to a precision we now know is absurd. Nonetheless, by the 1860s astronomers had arrived at numbers that weren't too far off from modern values. With those diameters and Laplace's masses, they

◀ **ICY JOVIAN TRIO** Three of the four Jupiter moons discovered by Galileo in 1610 are composed largely of water ice — a fact that eluded astronomers until the 20th century. Ganymede (upper left), Europa (far left), and Callisto (left), along with Io (not shown), are familiar targets for backyard telescopes.

GANYMEDE: NASA / JPL-CALTECH / SWRI / MSSS / KALLEHEIKKI KANNISTO; CALLISTO: NASA / JPL; EUROPA: NASA / JPL-CALTECH / SETI INSTITUTE



◀ **ICE HERE AND THERE** These cutaway diagrams show the differences in composition among Jupiter's four largest moons. Blue and white indicate water in solid (ice) or liquid form, while the metallic (iron, nickel) cores are shown as gray and rock is indicated with brown. Io is the one moon lacking significant water, and Callisto is thought not to have a metallic core.

could calculate the densities of the Galilean moons.

The second key indicator is albedo. Observers can estimate how bright a moon is by comparing it to a "nearby" star of known magnitude. However, without knowing the size of the satellite, it's not possible to tell if it's small but shiny (high albedo), or big and dusky (low albedo). Both would reflect the same amount of sunlight. Once we know the size of the moon, we can then determine its albedo.

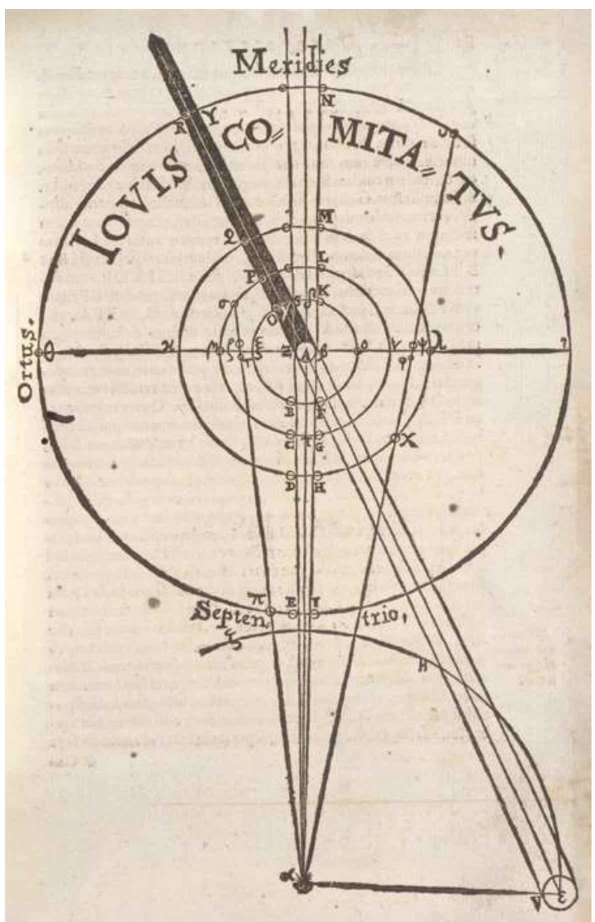
So now astronomers had the rudiments of the two indicators in hand. In the 1860s, pioneers in astrophysics like Fr. Angelo Secchi, S. J. identified the signatures of hydrogen and oxygen gases in stars' spectra, which suggested that water ice might be common in the universe. So, was some astronomer in the 19th century able to put all the pieces together and discover the icy natures of Callisto, Ganymede, and Europa? Nope! And the story of how they missed it is fascinating.

On Thin Ice

From the standpoint of the early 21st century, it's perhaps difficult to believe that there was ever a time when scientists simply weren't interested in knowing the compositions of the stars and planets. German astronomer Friedrich Wilhelm Bessel, for example, wrote in 1848 that astronomy "must lay down the rules for determining the motions of the heavenly bodies as they appear to us from the Earth"; other information, such as knowing the density, was, "not properly of astronomical interest." That meant that even with the correct data right in front of him, Bessel (and his contemporaries) might not even have thought to ask about the nature of Jupiter's moons. However, pioneers like Secchi and English astronomer William Huggins had begun to speculate on the compositions of the stars. Would some brave planetary scientist follow suit?

One way to gauge the state of knowledge of astronomers of the time is to read the books they wrote for popular audiences. Consider the 1873 edition of Reverend Thomas W. Webb's *Celestial Objects for Common Telescopes* and Simon Newcomb's widely read 1878 book, *Popular Astronomy*. What they say about Jupiter's moons is surprising. According to Newcomb, "The light of these satellites varies to an extent which it is difficult to account for, except by supposing very violent changes constantly going on on their surfaces." Newcomb was an accomplished astronomer at the U.S. Naval Observatory and should have been a reputable source, so where did he get this idea?

Webb, for his part, goes on at length, citing observers who noted radical changes in the brightnesses of the moons. For example, he writes about Callisto, "as far back as 1707 Maraldi noticed that, though usually faintest, it was sometimes brightest (a variation which he ascribes to all the satellites); in 1711 Bianchini and another once saw it for more than 1h so feeble that it could hardly be perceived; 1849, June 13 Lassell made a similar observation with far superior means . . ."



◀ **GALILEO'S MOONS** This illustration by the German astronomer Fr. Christoph Scheiner, S. J. and his student Johann Georg Locher shows Jupiter, its shadow, and its four largest moons. The diagram appeared in their book *Mathematical Disquisitions*, only four years after Galileo first discovered the satellites with his crude telescope. In the book they proposed that measuring the time required for the moons to pass through the planet's shadow, or across its disk, could provide more detailed information about the Jovian system.

Webb also cites other notable scientists, including German astronomer Rudolf Engelmann, England's John Herschel, and the famous Prussian lunar observers Wilhelm Beer and Johann Heinrich von Mädler. He even quotes Secchi, who described seeing the shapes of these moons as "irregular and elliptical." Indeed, many observers of the era reported various surface features on these satellites.

What are the chances they were seeing real features on Jupiter's moons? Not good. Perceiving the satellites as disks (as opposed to mere points of light) is one thing; seeing features on those disks is quite another. As most readers know, all telescopes have an inherent limit in their ability to resolve fine detail that depends on the diameter of the objective lens or mirror. Secchi's telescope had an aperture of 9.6 inches (24 cm), which gives it a theoretical resolution of about 0.5 arcsecond. Ganymede, the largest Jovian moon, never appears larger than 1.8 arcseconds across (1/1000 the diameter of the full Moon). To put it simply, seeing detail on Jupiter's moons requires a large telescope used under extremely favorable conditions (*S&T*: Jan. 2014, p. 54).

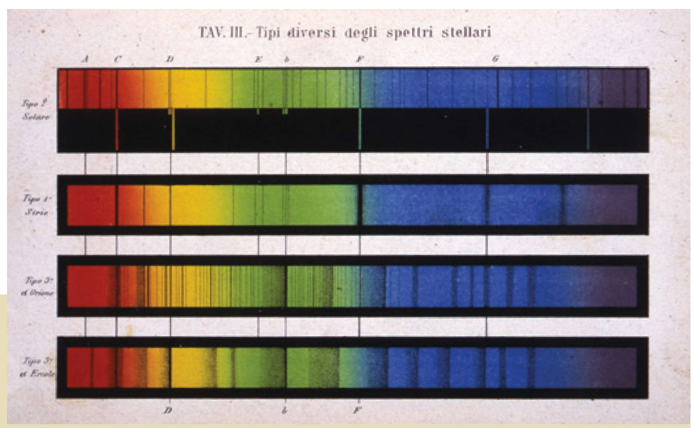
Despite the limitations of their instruments, 19th-century observers reported diameters for the moons within 10% of their actual values (accurate to about 1/10 arcsecond). Secchi's numbers, however, reflect a precision of 1/1000 arcsecond, and one of his Jovian moon drawings shows what appear to be polar caps like those seen on Mars — certainly not real features.

The preferred theory of the time to explain the moons' varying brightnesses invoked pancake-shaped objects that tumbled — one moment we might be seeing them edge-on and dim, and then later face-on and bright. And when they were in between edge-on and face-on, we'd see the moons as ellipses. Regardless of how strange this might sound today, at the time some astronomers truly thought they were seeing significant variations in the moons' brightnesses. And that would have made it impossible to determine their albedos, and therefore whether they were icy or not.

And what about density? Authors of astronomy books in the 19th century would often list each Jovian moon's mass and radius, but not bother to divide the mass by the volume to calculate their densities. The notable exception was English amateur astronomer George Frederick Chambers. His 1861 *A Handbook of Descriptive and Practical Astronomy* contains a wonderful table of sizes, masses, and densities for Jupiter's moons. However, his density figures look very odd — they're all only about 1/10 the density of water. Little in nature has that density. Gasses are far less dense than that. Everything else, even objects that float in water, are closer to water's density. Yet Chambers simply offers this information without comment.

What's surprising is that the numbers Chambers lists for size and mass are pretty good — close enough to have allowed him to compute moon densities that wouldn't be too far

▼ **COLOR VISION** The spectra of various stars as shown by the 19th-century Italian astronomer and pioneering spectroscopist Angelo Secchi. Presented here from top to bottom are the spectra of the Sun, Sirius, Betelgeuse, and Alpha Herculis (Rasalgethi). This work was the first systematic effort to classify stars by their spectra — Secchi observed about 5,000 stars — which led ultimately to the Hertzsprung-Russell diagram and our understanding of stellar evolution.



VATICAN OBSERVATORY

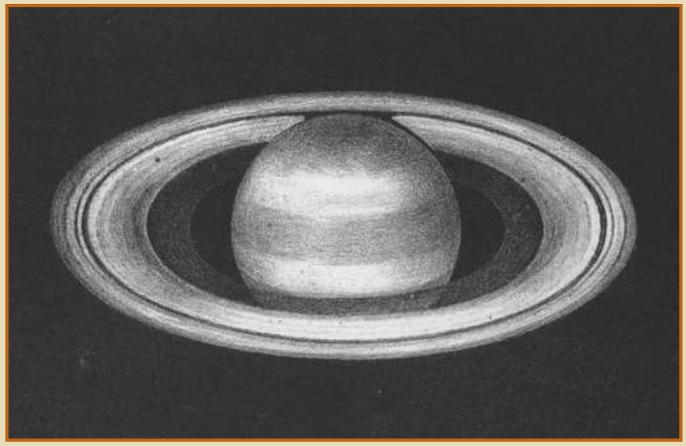
The Color of Ice

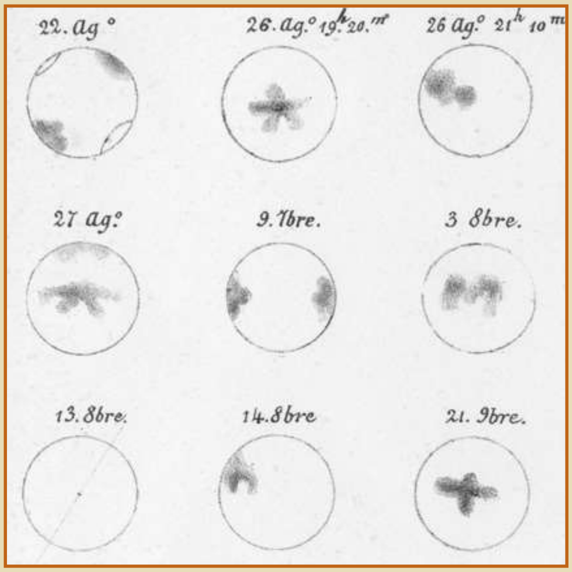
Why should low density and high albedo indicate the presence of water ice, instead of some other exotic material?

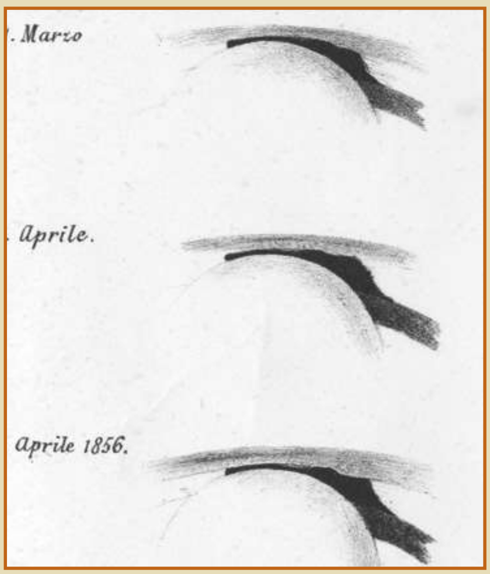
Firstly, water ice *should* be really common in the universe. This comes from knowing what the stars themselves are made of. Nineteenth-century pioneers in spectroscopy figured out how to split a star's light into its component colors, thus determining what elements are present. Angelo Secchi identified the spectral signature of hydrogen gas, and by the early 20th century, astronomers understood that stars are mostly composed of hydrogen, with helium coming in a distant second.

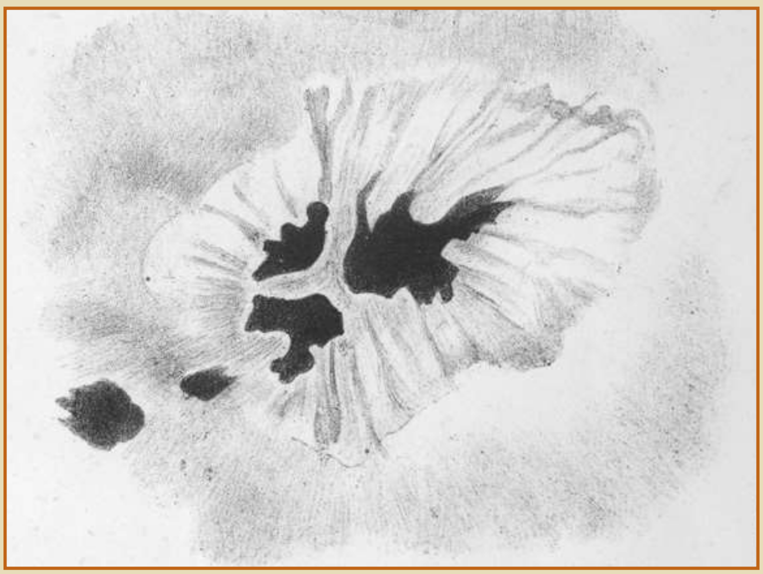
The most common elements after hydrogen and helium are oxygen, carbon, and nitrogen. Thus, the most common compounds in planets turn out to be water, methane, and ammonia — the chemicals that result from hydrogen reacting with oxygen, carbon, and nitrogen, respectively. In the outer solar system these compounds all freeze into ices. The easiest of these to freeze is water — we have snow and ice on Earth, at temperatures where methane and ammonia remain gasses. So it's reasonable to identify the low-density, high-brightness material in the moons of Jupiter as water ice.

In fact, water ice has a very distinctive spectral signature in infrared light. That was finally detected in the light from Jupiter's moons and Saturn's rings in the early 1970s, by competing teams of astronomers at the Massachusetts Institute of Technology and the University of Arizona.









VATICAN OBSERVATORY (6)

▲ **SOLAR SYSTEM SKETCHES** This series of drawings by Angelo Secchi shows (clockwise from upper left) Jupiter, Saturn, Mars, a sunspot, the shadow of Saturn's globe projected onto the rings, and, most notably, multiple sketches of Jupiter's moon Ganymede. The quality of Secchi's drawings, especially of Saturn, reveals his skill at making and recording observations; nevertheless, his 9-inch refractor could not resolve the detail shown on Ganymede's tiny disk. These renderings are from Secchi's "Descrizione del nuovo Osservatorio del Collegio Romano" in *Memorie dell' Osservatorio del Collegio Romano 1852–1856* (published in 1856).