2

A history of the exploration of Io

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"On the 7th day of January in the present year, 1610, in the first hour of the following night, when I was viewing the constellations of the heavens through a telescope, the planet Jupiter presented itself to my view, and as I had prepared for myself a very excellent instrument, I noticed a circumstance which I had never been able to notice before, namely that three little stars, small but very bright, were near the planet; and although I believed them to belong to the number of the fixed stars, yet they made me somewhat wonder, because they seemed to be arranged exactly in a straight line, parallel to the ecliptic, and to be brighter than the rest of the stars, equal to them in magnitude ... When on January 8th, led by some fatality, I turned again to look at the same part of the heavens, I found a very different state of things, for there were three little stars all west of Jupiter, and nearer together than on the previous night ..."

Galileo Galilei, *Siderius Nuncius*, March 1610
Translation by E. S. Carlos (Shapley and Howarth, 1929)

2.1 THE DISCOVERY AND EARLY OBSERVATIONS OF THE GALILEAN SATELLITES

2.1.1 From Medician Star to a world of its own

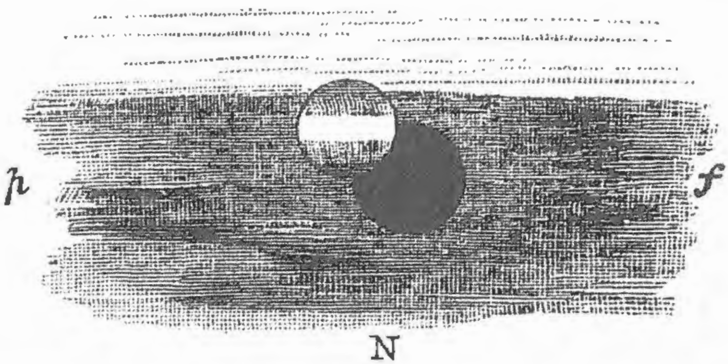
The history of the exploration of Io logically begins with Galileo's discovery of this and the other three large Jovian satellites in 1610, communicated in his *Siderius Nuncius* in March of that year. There is credible evidence for the assertion that the Bavarian astronomer Simon Marius (Mayr) independently found the satellites at about the same time, and perhaps 5 weeks earlier (Johnson, 1931; Pagnini, 1931), but his failure to communicate the discovery and the absence of a clear confirmation of the earlier dates gives Galileo the credit for the first detection. Marius never claimed priority in discovery over Galileo, but his suggested names for the four satellites have survived the centuries, despite some scholars' contrary expectations (Lynn, 1903), and thus we have Io, Europa, Ganymede, and Callisto, after various lovers of Jupiter.

The discovery observations were followed by determinations of the periods of the orbits around Jupiter; Io's synodic period is 42.477 hours, a value close to that determined by Galileo himself. The proportionality between the periods and distances of the satellites from Jupiter not only validated Kepler's laws of planetary motion (the third law was published in 1619), but it afforded a practical means to determine, by telescopic observations of the eclipses and transits, the longitude of an observer on Earth. Then, in 1675, Ole Roemer determined from observations of eclipses and transits that the events seen near opposition occur earlier than average, while those seen far from opposition occur later. He connected the observed differences in timing of the eclipse events to the differing distance of Jupiter from Earth, and correctly deduced that light propagates at a finite velocity, requiring some 16 minutes 26.6 seconds to cross one diameter of the Earth's orbit. The radius of the Earth's orbit (the Astronomical Unit, AU) was not known reliably until somewhat later, but when Roemer's time is used with the modern value of the AU, the resulting velocity of light ($\sim$303,300 km/sec) is within 2% of the value known today.

The motions of the four Galilean satellites attracted the attention of a number of observers and mathematicians in the 17th and 18th centuries. Both Galileo and Mayr prepared tables of the motions of the satellites, followed by G. B. Hodierna in 1656, and in 1668 by J. D. Cassini. Other improved empirical tables followed, and then Pierre-Simon Laplace published his mathematical theory of the orbits in 1788. With this work the importance of the resonant periods of Io, Europa, and Ganymede were recognized. The orbital period of Europa is twice that of Io, and Ganymede's period is twice that of Europa. This succession of 2 : 1 ratios of the orbital periods is known as a Laplace resonance. Dissipation of tidal energy through the 2 : 1 Io–Europa resonance is a direct cause of the continuously active volcanoes on Io that is discussed elsewhere in this chapter and book, while the 2 : 1 Europa–Ganymede resonance serves to keep the interior of Europa in a partially liquid state.

The unusual nature of Io as a physical body began to emerge as soon as telescopes became good enough to resolve the disk and attention turned to aspects of planetary satellites beyond their orbits and dynamics. In 1892, while measuring the diameters of the Galilean satellites with a visual micrometer, W. H. Pickering noticed that Io was distinctly elliptical in outline. He watched the elongated image slowly change orientation and concluded that Io has the form of an ellipsoid, a shape that he also saw in the other three large satellites (Dobbins and Sheehan, 2004). Other observers also noted anomalous appearances of Io. For example, when Io transits Jupiter's disk both the satellite and its shadow can clearly be seen against the planet's multi-hued clouds. Observing with the Lick Observatory 12-inch refractor[1] in 1890, E. E. Barnard (1891a)

[1] Barnard was denied regular use of the 36-inch refractor until August 1892; he discovered Amalthea, Jupiter's fifth satellite (and the first one since Galileo) just 1 month later on 9 September 1892 (Cruikshank, 1982).



Transit of Satellite I., 1893 Nov. 19; 36-in. Refractor.

Figure 2.1. Appearance of Io against the disk of Jupiter during the transit of 19 November 1893. Observed by E. E. Barnard with the Lick Observatory 36-inch refractor, and clearly showing the dark polar regions and bright equatorial band of Io (Barnard, 1894).

noted that in transit Io often appeared as a dark or dusky spot, and on September 8 of that year it appeared to him "... elongated in a direction nearly perpendicular to the belts of Jupiter." At higher powers and with perfect definition the satellite appeared distinctly double, the components clearly separated. Barnard's colleague and double-star expert, S. W. Burnham, verified the appearance of Io in transit as a double object. Barnard suggested that Io has a white belt on its surface, parallel to those of Jupiter, or that it is actually double; he was "... strongly inclined to favor the theory of actual duplicity." The idea of a double Io eventually disappeared upon closer scrutiny with larger telescopes and the clear circularity of the shadow when projected on Jupiter's clouds. The odd apparent shape of Io was later attributed to the distribution of light and dark material on the surface, and to distorted images produced in telescopes whose tubes confined air of nonuniform temperature. In modern images of Io the color differences across the surface are clearly visible. In high-definition photographs of Io in transit against a blue–white region of Jupiter (e.g., Minton, 1973), the red–brown polar caps of the satellite are clearly discernable by their color contrast to the equatorial regions and to the background of Jupiter's clouds. Barnard (1891b) had noted that "... if a bright belt existed on the satellite, it would have the effect of apparently cutting it into two parts, since the belt would be lost in the bright surface of Jupiter. The satellite would, therefore, appear as two dusky dots, which, through irradiation, would appear small and round." (Figure 2.1.)

While Pickering adhered to his assertion of the egg shapes of the Galilean satellites for his entire career (Dobbins and Sheehan, 2004), Barnard reached the correct conclusion and moved on (Sheehan, 1995). He later used the Lick Observatory 36-inch telescope to measure the diameters of all the planets and satellites with a visual micrometer and reported the diameter of Io as 1.048 arcsec (Barnard, 1897), corresponding to 3,950 km, about 8.5% larger than the presently accepted mean diameter of 3,642 km. Barnard's measurements followed those of an early visitor to Lick Observatory. Albert Michelson (1891) used the 12-inch Lick refractor (stopped down to 6 inches) in a very early application of his interferometric technique, later used to measure the diameters of stars. Michelson's diameter for Io was 1.02 arcsec, or about 3,844 km.

In order to refine the orbits of all four Galilean satellites, visual photometric observations of the eclipses of the Galilean satellites began in 1878 (Pickering, 1907). The observer determined the time of the midpoint of the disappearances into, and reappearances from, Jupiter's shadow, by plotting the changing brightness until the satellite became invisible (disappearances) or regained full brightness (reappearances). These observations formed the basis for the *Tables of the Four Great Satellites of Jupiter* (Sampson, 1910).

Additional interest attaches to the eclipse curves, particularly on the disappearance of the satellites into the shadow, because while the timing depends on a satellite's orbit, the exact shape of the curve depends upon the diameter of the satellite, the geographic distribution of its surface brightness (albedo), and refractive layers in Jupiter's upper atmosphere (Harris, 1961). The occasional observation of an enduring brightness "tail" at about stellar magnitude 14 of a satellite entering Jupiter's shadow was taken as evidence for a refracting layer in Jupiter's atmosphere (Harris, 1961, and G. P. Kuiper's appendix III to that article). We return below to other aspects of eclipse phenomena.

The overall color of Io attracted early attention. Kuiper (1973) notes that Hertzsprung discovered the unusually orange color in 1911, although W. H. Pickering had remarked on it in 1893 (Dobbins and Sheehan, 2004). The earliest photoelectric photometry (Stebbins, 1927; Stebbins and Jacobsen, 1928) confirmed the dramatic color difference (in $B–V$)[2] of Io in comparison with the other three Galilean satellites, and gave the first quantitative information on the rotational brightness variations as well as the change in brightness with solar phase angle (the solar phase function). It also established with clarity the synchronous rotation and revolution of these satellites by the repeatability of the brightness curves with orbital position. The solar phase function, in turn, enabled early calculations of the photometric properties of the surfaces, using scattering theories derived by Minnaert (1941), van de Hulst (1957), and others.

2.2 WHAT IS THE NATURE OF IO?

2.2.1 A paradigm emerges

At this point in the story, we introduce a theme to which we will return along the way. This is the theme of the changing paradigm of our understanding of Io as new ideas

[2] The letters U, V, B refer to a color filter system that astronomers use to measure the brightness of an astronomical source at three different colors, or bands, of the spectrum, ultraviolet (U), blue (B), and visual (V). The wavelengths of the bands are $U = 0.35\,\mu m$, $B = 0.435\,\mu m$, and $V = 0.555\,\mu m$. The differences in intensity of the light transmitted at each of these wavelengths provides a measure of temperature of an incandescent source (a star) and of the spectrum of a planetary object that shines by reflected sunlight. The spectrum of a planetary object is an important indicator of its composition.

and new data have been brought to bear on this object as an individual body, and as a member of the set of four Galilean satellites.

With information about the approximate sizes of the Galilean satellites and estimates of their masses from orbital dynamics, early values for their mean densities were calculated. The venerable astronomy textbook by Russell, Dugan, and Stewart (1945) listed the mean densities as 2.7, 2.9, 2.2, and 1.3 g/cm^3, for Io, Europa, Ganymede, and Callisto, respectively.[3] These or similar early values for the densities, together with the emerging information on the density and composition of Jupiter, were the starting point for speculation on the compositions of the Galilean satellites. Jeffreys (1923) noted that the densities are too low for metal and rock, and suggested that the satellites are made primarily of liquefied gases of the same sort constituting Jupiter, a view reached also (and apparently independently) by Tammann (1931 [quoted in Wildt, 1969]). The early values of the densities of the four satellites, while indicative of the presence of volatile material, were not accurate enough to reveal the striking trend of the high density of Io (3.53 g/cm^3) compared with the low value for Callisto (1.85 g/cm^3) that we know today (see below).

Considerations of the physical make-up of the Galilean satellites arose primarily in connection with calculations of the compositions of the four giant planets. At the same time, an increasing interest in the compositions of the rocky planets (including asteroids), and particularly the Moon, arose on the part of geochemists (e.g., Brown, 1949; Urey, 1952; Suess and Urey, 1956). Interest in the Moon was energized by the approaching era in which humans would have the ability to send probes there and to other planets. Thus, an intense interest arose in the geosciences community in the study of the planets, a subject formerly reserved for the field of astronomy. World War II had advanced the field of rocketry from a series of back yard science experiments to major government enterprises both in the United States and the Soviet Union. The primary motivation for rocket development concerned the intercontinental ballistic missile, but scientists had the cosmos in view.

Nobel Laureate Harold Urey was one of the early founders of planetary science. His interest in geochemistry led him to a closer examination of the planets in the context of two broad chemical classes; the four inner planets with properties generally similar to those of the Earth, and the four gas giants with their profoundly different chemical character. The outer planets all have atmospheres and low-density interiors which are chemically reduced,[4] while the inner planets have crusts of silicate rocks and oxidized atmospheres. The Moon's properties are similar to those of Earth, and by extension it might be reasonably assumed that the moons of the outer planets mimic the properties of their parent bodies. Thus, a paradigm emerged which held that objects in the outer Solar System were chemically reducing, most likely as a

[3] The earlier 1926 edition of Russell, Dugan, and Stewart listed the densities as 2.9, 2.9, 2.2, and 0.6 g/cm^3 for Io through Callisto, respectively. They suggested that the first two are composed of rock, like the Moon, and the outer two may be composed largely of ice or solid carbon dioxide.

[4] Wildt (1932) had identified bands in the spectra of Jupiter and Saturn (discovered in 1905 by V. M. Slipher) as methane and ammonia, the simplest reduced molecules of carbon and nitrogen. Herzberg (1952) identified molecular hydrogen in the atmosphere of Uranus and Neptune, and by implication, in the atmospheres of Jupiter and Saturn.

consequence of their greater distance from the Sun which made them cooler and permitted the retention of the lighter molecular weight reducing gases.

The interpretation of the many unusual observations of Io that began after the end of World War II was strongly influenced by the pre-space age paradigm which held that Io, as a body in the outer Solar System, had to be *reducing* in nature. At the same time, the cosmochemical models suggested that water ice would be a major rock on the surfaces of outer Solar System bodies of Io's size (e.g., Urey, 1952).

2.2.2 New technology enables new observations

Harris and Kuiper (Harris, 1961) conducted the next extensive broadband photometric study of Io and the other satellites with greatly improved photoelectric detectors and the McDonald Observatory 82-inch telescope in 1951–1954. They transformed the Stebbins and Jacobsen measurements to the *UBV* system, and corroborated the significant brightness and color variations seen as Io rotates, deriving the mean opposition magnitude $V_o = 4.80$, and variations of 0.18 mag in *B–V* and 0.5 mag in *U–B* colors.

Another extensive photometric study was undertaken by Morrison *et al.* (1974; see also the review in Morrison and Morrison, 1977) in the *UBVY* system (intermediate filter bandwidth) resulting in further refinement of the solar phase function and colors.

Just as detectors were improving throughout the 1950s and 1960s, so were interference filters that permitted higher throughput and narrower photometric passbands. Johnson and McCord (1971) used a photometer with 24 narrow-band filters to define the spectral reflectances of the Galilean satellites with higher spectral resolution than had previously been accomplished, finding a broad absorption in Io's reflectance of between 500 and 600 nm. With the higher spectral resolution afforded by the 24 filters, Johnson (1971) noted the steep red slope in Io's reflectance between 300 and 400 nm, and combined his own photometry with earlier work to derive phase integrals and Bond albedos of all the Galilean satellites.

The strong color and the absorption at 500–600 nm were corroborated in subsequent spectrophotometry with a series of narrower filters by Wamsteker (1972), and in an unpublished paper by Wisniewski and Andersson (1973).[5] In the Wisnewski and Andersson work, a silicon vidicon detector was applied to a prism spectrometer to give 500 spectral channels from 400 nm to 1.0 μm. In Figure 2.2 we reproduce the two spectra of Io from the unpublished manuscript.

The long wavelength limit of the early photometry and spectroscopy was imposed

[5] The unpublished paper (see references) was approved and accepted for publication by G. P. Kuiper for the *Communications of the Lunar and Planetary Laboratory*, which he edited. The proofs are dated December 1973, the month in which Kuiper died. Following Kuiper's death, the *Communications* ceased publication, and several manuscripts that were in publication were abandoned. Wisniewski sent a copy of the proofs to Cruikshank on 24 June 1975, lamenting that the paper, which included spectra of all four Galilean satellites and Titan, remained unpublished. Both Wisniewski and Andersson have since passed away.

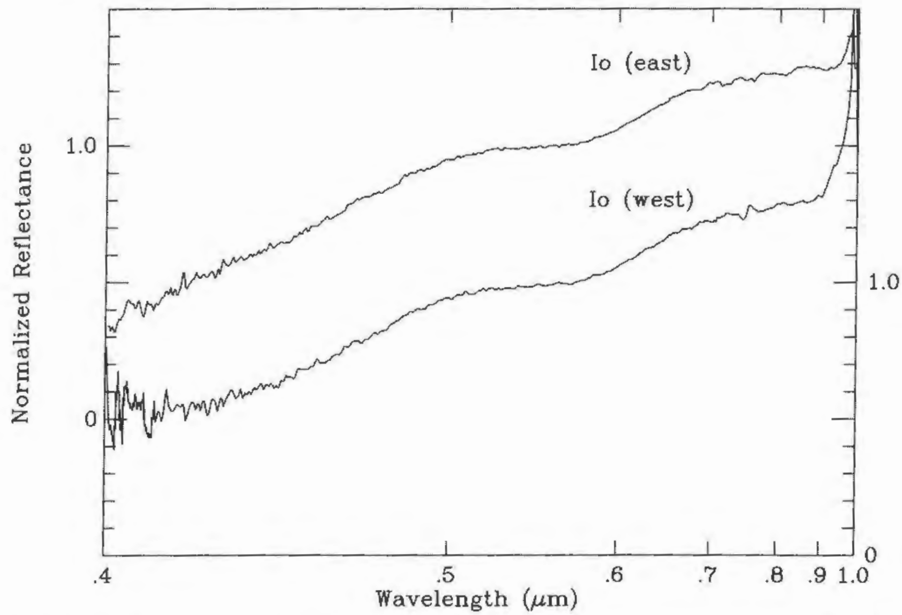


Figure 2.2. Normalized spectra of Io at western and eastern elongations in 1973, ratioed to a solar-type star (Wisniewski and Andersson, 1973, unpublished). These spectra confirm the broad absorption, 500–600 nm, first noted by Johnson and McCord (1971). The scale on the left abscissa refers to Io (east), and that on the right refers to the plot for Io (west). Reproduced courtesy of the Lunar and Planetary Laboratory, University of Arizona.

by the limitations on the photo detectors and photographic emulsions, which extended to ~1.2 μm. Photoconductor detectors developed during the war and declassified in 1945 were quickly adapted to astronomical work (Kuiper *et al.*, 1947) and the modern era of infrared astronomy was born.[6] Johnson and McCord (1971) extended the spectral reflectance observations of all four satellites longward in wavelength to 2.5 μm with an additional set of filters, showing that Io's reflectance remains high and nearly constant from ~0.7 to 2.5 μm. This property is in strong contrast to the reflectances of the other three satellites, as had been noted in the first studies with infrared detectors and prism spectrometers accomplished by Kuiper (1957) and Moroz (1966). Those earliest observations by Kuiper and Moroz led each investigator to propose independently that H_2O ice is a major constituent of the surfaces of Europa and Ganymede; Kuiper (1957) published his conclusion that the reflectances are consistent with H_2O ice only briefly and without any figures in an abstract, while Moroz (1966) published the first spectra (Figure 2.3).

[6] Earlier infrared observations of the Moon, planets, and a few astronomical sources had been possible with detectors sensitive at wavelengths beyond ~10 μm, but these had insufficient sensitivity to detect fainter sources or to obtain spectra of any but the brightest objects in the sky.

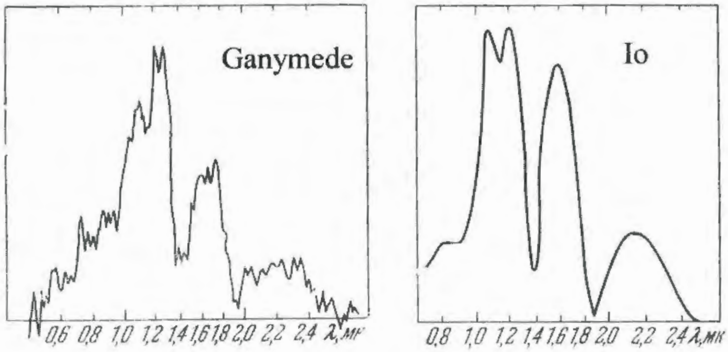


Figure 2.3. Spectra of Io and Ganymede (0.7–2.5 μm) obtained on 15 October 1964 by V. I. Moroz (1966) with a scanning prism spectrometer. The *y*-axis is brightness.The Ganymede spectrum is the record of a single scan through the spectrum, while the Io spectrum is the average of four. These spectra are not ratioed to the solar spectrum: the greater relative heights of the 1.6- and 2.2-μm peaks in the Io spectrum, where H_2O ice is absorbing, relative to those on Ganymede, indicate the absence of H_2O ice on Io.

Kuiper (1973) eventually published his spectra of the Galilean satellites in a review he wrote after the publication of two papers in which high-quality spectra clearly showed individual bands of H_2O ice on Europa and Ganymede (Pilcher *et al.*, 1973; Fink *et al.*, 1973).

The first near-infrared observations of the Galilean satellites beyond 2.5 μm were reported by Gillett *et al.* (1970), who found that the reflectance of Io at 3.5 and 4.9 μm is significantly higher than that of the other three. Although Io was clearly different from the others, the authors demurred, noting that, "The interpretation of the apparent absorption feature in the 3–5.4-μm spectrum of satellites J II–J IV coupled with the absence of absorption of like magnitude in the spectrum of J I, which retains its extremely high albedo, is beyond the scope of this paper." Lee (1972) also observed the satellites in the near-infrared out to 3.6 μm and also noted the large difference between Io and the others. Lee worked at the University of Arizona's Lunar and Planetary Laboratory, and was aware of the laboratory studies of sulfur and its compounds then in progress by G. T. Sill (1973) at the same institution. Lee concluded that the high albedo at 3.4 μm "... is compatible with a sulfur compound. The drop in the curves for Europa and Ganymede confirms earlier conclusions that H_2O ice is present on these satellites [Kuiper, 1957] ..."

Note that at this point the H_2O ice bands on Europa and Ganymede had not been clearly resolved, and arguments for its presence on these two bodies (and its absence on Io) were based on the relative shapes of the reflectance curves rather than the detection of specific bands.

Other post-war improvements in detectors and filters included those suited to thermal measurements of astronomical sources in the 8–14-μm spectral region (the 10-μm, or N band), corresponding in wavelength to a transparent "window" in the Earth's atmosphere. Using the Palomar mountain Hale 5-m telescope, then the largest in the world, Murray *et al.* (1964) set out to measure the brightness temperatures of the Galilean satellites. They detected thermal emission from Ganymede and Callisto, but could not detect Io or Europa because of their lower temperatures (<135 K and <141 K, respectively); those lower temperatures are a consequence of their high albedos in the visual region of the spectrum where relatively more sunlight is reflected. Io was eventually detected in the 10-μm band (e.g., Gillett *et al.*, 1970), and then Morrison *et al.* (1972) measured its flux in the 20-μm band, a more difficult task because of the lesser transparency of the Earth's atmosphere at that wavelength. The 20-μm (Q) band is closer to the black-body flux peak for an object of Io's temperature, but Io's 20-μm brightness temperature (127 ± 3 K) found by Morrison *et al.* (1972) is less than the predicted black-body equilibrium temperature; the authors suggested that Io's emissivity might be less than unity. (In Section 2.3.5 we discuss the detection of anomalously *high* thermal emission from Io at shorter wavelengths.)

Further progress in studying the thermal properties of Io and the other Galilean satellites was achieved with infrared measurements during the eclipses, when sunlight is quickly cut off and the surfaces rapidly cool, and when the surfaces warm after the restoration of sunlight (Morrison and Cruikshank, 1973; Hansen, 1973). It was seen from these studies that a thin (few millimeters) layer of highly insulating, low-density material overlaying a thicker, denser material (ice or rock) could approximately explain Io's (and the other satellites') changes in temperature during eclipses. This behavior shows that Io's surface has a significant thermal inertia, which is a measure of the degree of departure of the actual surface temperature from the temperature of a gray body in instantaneous equilibrium with the insolation. Thermal inertia is related to the surface microstructure, insulating properties, and layering of different materials of different densities and textures. The thermal studies could not clearly distinguish between rocky material and ices, in part because of a lack of laboratory data on the thermal properties of such materials in a vacuum.

2.2.3 Io eclipse phenomena at optical wavelengths

Because the eclipse disappearance and reappearance events for Io as seen from Earth all occur very close to Jupiter (less than one Jupiter radius, or <20 arcsec), scattered light from the planet affects the accuracy of the brightness estimates of Io, and generally more so than for the other satellites, whose eclipse phenomena mostly occur at larger angular distances. The eclipse curves for Io in the visual photometry by Pickering (1907) and others show increased scatter in the points, particularly around maximum brightness, compared with the curves for the other satellites. In several Io reappearance curves, there appears to be an overshoot in brightness, such that the satellite's brightness appears too high when it first emerges from the shadow, and then after a few minutes dims a bit and remains constant. These irregularities in the eclipse curves might logically be attributed to the increased scatter in the data because of the interference of the light from Jupiter itself.

An anomalous brightening of Io by about 10 per cent for 10–20 minutes following its emergence from Jupiter's shadow was first observed with a photoelectric photometer by Binder and Cruikshank (1964), who proposed that an atmospheric component

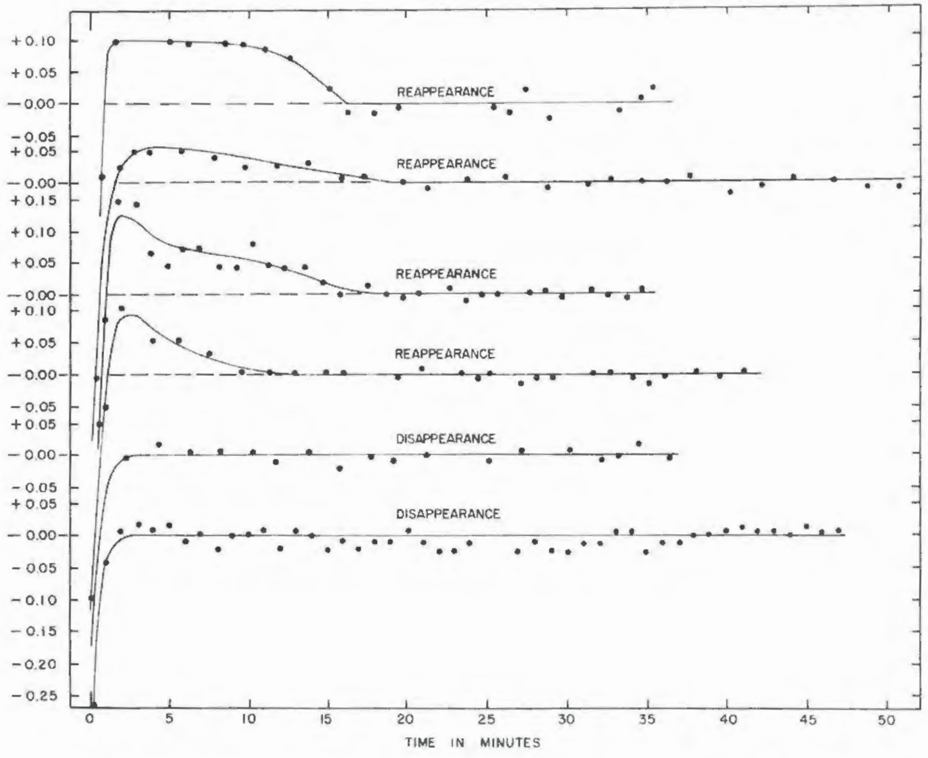


Figure 2.4. Photometry of Io eclipse reappearances and disappearances in 1962 and 1963 (Binder and Cruikshank, 1964), showing the reported post-eclipse anomalous brightening in the top four traces. No brightening effect was seen at similar geometries at the disappearance events. Reproduced courtesy Elsevier.

condenses on the surface of Io during the eclipse, and then evaporates a few minutes after the restoration of sunlight (Figure 2.4). Their 1964 paper predated the discovery of volcanic SO_2 gas constituting Io's thin and variable atmosphere, and Kuiper (1949) had placed upper limits of 200 and 40 cm-atm of gaseous methane and ammonia, respectively, for all the satellites from his spectroscopic observations. Subsequently, the anomalous brightenings have been seen by some observers (e.g., Johnson, 1971), while others found no anomaly at other eclipse reappearances. Nelson *et al.* (1993) reviewed much of the earlier literature and report observations of 14 eclipse reappearances from 1981–1989, finding modest anomalous brightenings of a few per cent at some events.

Later observations from space offer an improved situation *vis-à-vis* the scattered light from Jupiter. Observations of a few eclipse events by *Voyager* (Veverka *et al.*, 1981), *Galileo* (Buratti *et al.*, 1995; Simonelli *et al.*, 1998), and the Hubble Space Telescope (HST) (Secosky and Potter, 1994) have shown no global brightenings, although certain regions of the disk may have changed in brightness.

After the discovery of SO_2 frost on Io's surface (see Section 2.4.1) and with the knowledge that Io's atmosphere of gaseous SO_2 is variable in density on both spatial and temporal scales because of the active volcanoes, Fanale *et al.* (1981) calculated that any eclipse condensations are necessarily sporadic. The fully saturated atmosphere contains sufficient SO_2 to cause condensation of an optically thick layer only in some locations and at some times. They also found that the rapid evaporation time of $\sim$15 minutes is in agreement with the amount of SO_2 that would be returned to the atmosphere when sunlight was restored at the end of the eclipse. Scattering calculations indicate that a layer several millimeters thick is needed to achieve the required optical thickness, and such a layer would probably not evaporate in 15 minutes. Nelson *et al.* (1993) therefore concluded that the condensation/sublimation scenario is only marginally possible.

As a modern sequel to the saga of Io's anomalous eclipse behavior, when the *Cassini–Huygens* spacecraft flew by Jupiter in December, 2000, en route to Saturn, the Visible–Infrared Mapping Spectrometer (VIMS) instrument detected an apparent variation of the strengths of absorption bands of SO_2 ice in Io's spectrum from observations made before and after an eclipse. Bellucci *et al.* (2004) interpreted the changed band strength and an observed change in continuum brightness level as the condensation of atmospheric SO_2 gas as frost on Io's surface during the $\sim$2.5-hour eclipse. Subsequent time-resolved spectra of Io were obtained for five eclipse reappearances in 2004 (Cruikshank *et al.*, 2006), and at none of those events was there any observed change in the strengths of the several absorption bands of SO_2 ice in Io's spectrum.

Thus, the anomalous post-eclipse brightening of Io's surface remains unresolved. While the nominal atmospheric abundance of SO_2 gas is insufficient to condense into an optically thick surface layer during eclipse, it is marginally possible that local and temporal gross enhancements of SO_2 gas are sufficient to do so, at least in specific regions of the satellite's surface. Observing with the HST, McGrath *et al.* (2000) found enhanced SO_2 gas concentration above the Pele volcanic region, but the calculated abundance is less than that required for short-term condensation of a layer of sufficient optical thickness to produce the eclipse effect.

A response of Io's far-ultraviolet emission from the atmosphere during and after eclipse has been found by several investigators. Saur and Strobel (2004) have modeled the variation of the electrodynamic interactions of Io's atmosphere and ionosphere with the magnetosphere as an eclipse takes place, and predict that a delay in the plasma interaction when sunlight is restored after an eclipse can result in a post-eclipse brightening in the emission at far-ultraviolet wavelengths. Their model shows that the eclipse behavior at these wavelengths can clarify the relative contributions to Io's atmosphere of volcanic gases and gases derived from the sublimation of surface frost.

Although the post-eclipse brightening of Io and its interpretation are still disputed, the report by Binder and Cruikshank in 1964 called attention to the possibility that Io is not the atmospherically and geologically dead object that its small size and distance from the Sun would suggest. Accordingly, over the years Io has offered a number of surprises that continue to the present day.

2.2.4 Other reports of unusual behavior

A report by Kalinyak (1965) of unidentified and non-solar absorption lines in the visible-region spectra of Io, Europa, and Ganymede proved to be anomalous. Those data were obtained in 1963 with one of the early image tubes that electronically intensified the incident light, while apparently introducing flaws that were interpreted as absorption lines. Binder and Cruikshank (1966) obtained spectra in the same spectral region as Kalinyak's data with higher resolution, using conventional photographic techniques, and could not corroborate the features that had been reported. In the spectra by Binder and Cruikshank, one can see that the Na-D lines in the spectrum of Io are slightly less dark than the Na-D lines in the other satellites, although this was unnoticed at the time. Brown (1974) later discovered emission cores in the Io Na-D lines, leading to the characterization of Io's sodium cloud. We return to this discovery in Section 2.3.2.

A newspaper report in *Pravda* (7 January 1966) told of the discovery of atmospheres on the Galilean satellites at the Astrophysical Institute in Kazakhstan, but gave no details. We have been unable to find any further information or follow-up on this report.

Somewhat earlier, Jeans (1925, p. 348) mentioned in his book on the dynamical theory of gases that "An atmosphere has been observed on Titan", and that there are "suspected atmospheres on two of Jupiter's satellites". In his paper reporting the spectroscopic discovery of methane on Titan, Kuiper (1944) noted his puzzlement at Jeans' statement, and was unable to discover the source of those remarks.

2.3 THE *PIONEER* MISSIONS

2.3.1 A new view of Io

Observations of the Jovian satellites from space-based platforms began in the early 1970s with the launch of the *Pioneer 10* and *11* spacecraft to the outer Solar System. These spacecraft, each with mass of 258 kg, passed Jupiter in 1973 and 1974. The 25-kg instrument packages on each spacecraft included three remote-sensing instruments (an ultraviolet photometer, and imaging photopolarimeter, and an infrared radiometer), each providing important information about Jupiter and its atmosphere. The remote-sensing information about Io was limited to rather low spatial resolution, due in part to the fact that the spacecraft were spin-stabilized. However, the *Pioneer in situ* instruments provided important new results on the Io environment that had a significant impact on efforts to understand the nature of its interior, surface, and atmosphere. The *Pioneer 10* and *11* probes found that Jupiter has intense belts of charged particles, similar to the terrestrial Van Allen radiation belts, and that they are created by the Jovian magnetic field. The intensity of this radiation was found to be particularly high at Io's distance from Jupiter where atomic particles continuously impact the satellite's surface (Simpson *et al.*, 1974, 1975; Van Allen *et al.*, 1974, 1975;

Trainor *et al.*, 1974, 1975; Fillius and McIlwain, 1974; Fillius *et al.*, 1975). These discoveries spurred the development of a series of models involving radiation-induced modification of Io's surface and ejection of significant amounts of material from the surface into the Jovian magnetosphere.

The *Pioneer* results provided improved masses of the Galilean satellites by analysis of the slight gravitational deflection in the trajectory of each spacecraft as it passed each member of the Jovian system. Io was found to have a significantly higher density than the other Galilean satellites, and the trend of decreasing density of these bodies with increasing distance from Jupiter became clear (Anderson *et al.*, 1974). The values now in use are: Io 3.53, Europa 2.99, Ganymede 1.94, and Callisto 1.85 g/cm^3. Pollack and Reynolds (1974) explained the density trend quite elegantly by showing that the satellites formed rapidly during Jupiter's initial contraction phase when the planet was orders of magnitude more luminous than at present. Io's higher density shows that it is depleted in volatile components in comparison with the other Galilean satellites; this result served as an important input to, and constraint on, subsequent Io paradigm development.

We previously mentioned that Kuiper in 1957 and Moroz (1966, 1967) reported that the infrared spectra of Ganymede and Callisto were similar to the rings of Saturn, and therefore suggested that their surfaces were dominated by water ice. Both Kuiper and Moroz found that Io was different; instead of a drop in near-infrared reflectance toward 2.5 μm, the albedo remained high and fairly constant. A decade later, spectra of much improved quality clearly established that Io differs from the other Galilean satellites by a very high infrared spectral geometric albedo, and that it does not show any trace of absorption bands due to water ice of the kind found on the other Galilean satellites (Pilcher *et al.*, 1973; Fink *et al.*, 1973). The fact that Io was lacking the slightest trace of water, while water (as ice) dominated the surface of its companions, strongly influenced the pre-*Voyager* paradigm, which predicted that all small bodies in the outer Solar System would have surfaces dominated by water ice.

In 1971, Io passed in front of the star Beta Scorpii as seen from Earth; measurement of the attenuation of light from the star revealed a very low upper limit to Io's atmosphere (Smith and Smith, 1972; Bartholdi and Owen, 1972) and also permitted its diameter to be measured with high precision. The result (3,656±5 km, Taylor, 1972) is in remarkably good agreement with the currently accepted mean diameter (3,642±5 km). Later, when *Pioneer 10* passed behind Io in 1973, the attenuation of a radio signal from the spacecraft established that Io has an ionosphere, implying a very thin atmosphere with pressure about 10^{-7} bar (Kliore *et al.*, 1974, 1975).

In another great achievement, the *Pioneer* ultraviolet photometer detected a torus of hydrogen ions filling Io's orbit around Jupiter (Carlson and Judge, 1974).

The *Pioneer* missions triggered an era of intense interest in the outer planets, driven in part by the excitement generated by the *Pioneer* results, but also by a rare alignment of the outer planets which was to occur in the late 1970s. This configuration of the planets, which occurs at intervals of 150–175 years, would permit a spacecraft to fly past each giant planet in succession, using each planet's gravitational field to accelerate the spacecraft toward the next planetary rendezvous. This gravity-assist trajectory permitted the launch of a much larger spacecraft for the same size rocket than would otherwise be possible. NASA proposed and the United States Congress approved two *Voyager* missions to the outer Solar System to be launched in 1977. The *Voyager* spacecraft each had a mass of 815 kg and 11 scientific investigations which included four remote-sensing instruments.

2.3.2 Io and Jupiter's magnetosphere

Radio bursts from Jupiter had been observed for several years at decametric wavelengths leading up to the report by Bigg (1964) that these burst are linked to Io's orbital position. This was the first indication of the electrodynamic connection between Io and the Jovian magnetosphere. The observations were followed by theoretical investigations by Piddington and Drake (1968), Goldreich and Lynden-Bell (1969), and others.

The first observations that drew a close connection between the Jovian magnetosphere and the physical properties of Io itself were the high-resolution optical spectroscopic studies by Brown (1974) and Brown and Chaffee (1974) in which emission in the sodium-D lines was discovered (Figure 2.5). While it was soon found that the emission comes from a large volume of space surrounding Io, it also emerged that Io's surface is the source of atoms which are ejected from the surface and then excited by the Sun through resonant scattering (Matson *et al.*, 1974). Potassium emission was soon found (Trafton 1975), and the third neutral species, oxygen, was detected spectroscopically by Brown (1981). These neutral atoms form a cloud around Io extended along part of the satellite's orbit, and from this cloud the atoms are ionized and swept away by Jupiter's rotating magnetic field. It was at first thought that the neutrals were largely sputtered from the surface by incident magnetospheric particles, however the later discovery of high-temperature silicate volcanoes on Io opened the possibility that some material is ejected directly into space through that mechanism.

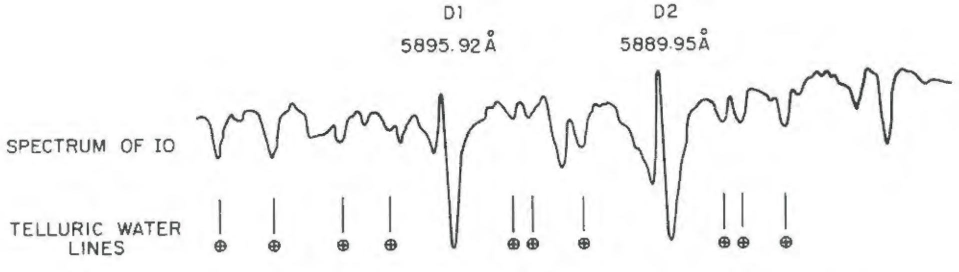


Figure 2.5. Narrow emission components are seen in the Na-D lines in this high-resolution spectrum of Io by Brown (1974), obtained with an echelle spectrograph.

2.3.3 Io week, November 1974

With the discovery of sodium emission on Io and the *Pioneer 10* occultation results, the pace of discoveries had risen to a level that merited a concerted effort on the part of observers worldwide. There was a growing feeling in the planetary science community that Io and its interaction with the circum-Jovian environment were responsible for a range of unique phenomena. Accordingly, Robert A. Brown, then at Harvard University, organized an international "Io week" for the period 6–16 November 1974. Radio astronomers, optical, and infrared observers from 16 countries on 6 continents responded, and most participated in making new observations. Brown then convened a one-day workshop at Harvard "... to discuss recent Io observations in the context of the current 'information explosion' in the study of the Galilean satellites." At least 10 presentations reported on radio, optical, and infrared measurements, together with modeling studies. This brief meeting focused attention on the unique properties and behavior of Io as perceived some 4 years before the first *Voyager* encounter. Odd as Io seemed at the time, the discovery of active volcanism in 1979 still came as a great surprise.

2.3.4 A new model for the composition of Io – the evaporite hypothesis

Io's distinctive spectral geometric albedo at visual wavelengths, along with the absence of water absorption features in the infrared spectrum formed the principal body of evidence from which the composition of Io's surface could be modeled or constrained. The absence of a thick atmosphere and its position within the Jovian magnetosphere suggested that charged particles bombard Io's surface, sputter material from the surface to the magnetosphere, and alter the chemical properties of the surface. Species found in the magnetosphere, sodium, potassium, and later sulfur, were also expected to dominate the compounds on the surface. This integrated body of evidence permitted synthesis of the post-*Pioneer*, pre-*Voyager* models of Io's surface.

One proposed explanation of Io's strong ultraviolet absorption shortward of 400–500 nm was the presence of elemental sulfur S_8 on its surface because laboratory reflectance spectra were found to have approximately similar absorption properties shortward of 500 nm (Wamsteker, 1972; Kuiper, 1973; Wamsteker *et al.*, 1974). Other materials with high infrared reflectivity were needed in addition to sulfur to match Io's reflectance properties, and suitable candidates were sought in the laboratory. In an effort to provide an integrated explanation of the available evidence, Fanale *et al.* (1974) proposed that Io's surface was an evaporate deposit consisting principally of sulfur, and halite (NaCl). They noted that Io's spectrum is similar to a leach product from the Orgueil meteorite, and pointed out the consistency of the evaporite deposit hypothesis with the absence of spectral features due to water in Io's infrared spectrum. They noted furthermore that halite, when irradiated while at low temperatures exhibits an absorption band at about 560 nm as a consequence of the formation of a metastable color center. This radiation-induced absorption feature at 560 nm could explain the spectral feature seen at that location in Io's spectrum (such a feature

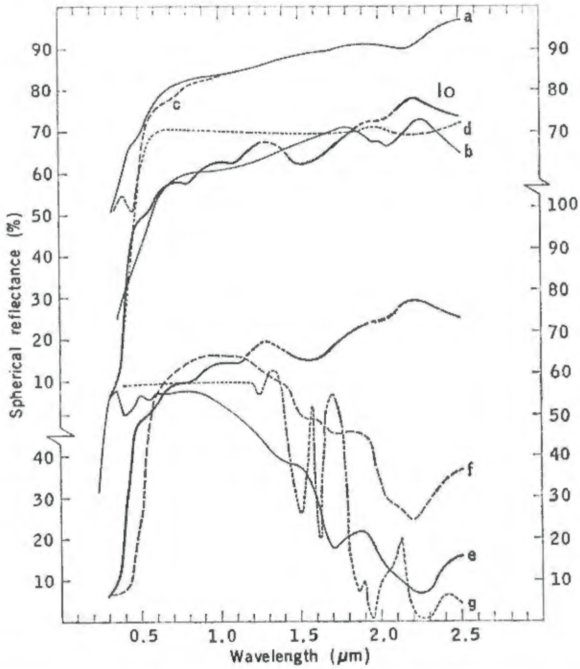


Figure 2.6. Comparison of Io's spectral geometric albedo and laboratory spectra of halite (a), a leach product from the Orgueil meteorite (b), and selensulfur (d) (after Fanale *et al.*, 1974). The evaporite model was a principal foundation of the pre-*Voyager* paradigm for Io. It addressed Io's spectral features, and the relationship between Io's surface and its magnetosphere by positing that Io's surface was composed of evaporite materials.

is not found in laboratory spectra of elemental sulfur, S_8). The comparison between Io's spectral geometric albedo and the laboratory spectra of the hypothesized surface materials is shown in Figure 2.6 (after Fanale *et al.*, 1974).

A consensus developed within the planetary science community around the evaporite hypothesis and it serves as the best example of the pre-*Voyager* paradigm. The evaporate hypothesis was explored in greater detail by many investigators using various combinations of elemental sulfur, many different salts, and other evaporite materials. Nash and Fanale (1977), after a lengthy study of the reflection spectrum of S_8 in mixtures with various combinations of candidate materials, including an attempt to simulate Io's radiation environment, found a best match to Io's spectrum to be a mixture of "... a fine-grained particulate mixture of free sulfur (55 vol%), dehydrated bloedite [$Na_2Mg(SO_4)_2 \bullet H_2O$] (30 vol%), ferric sulfate [$Fe_2(SO_4)_3 \bullet xH_2O$)] (15 vol%), and trace amounts of hematite [Fe_2O_3]". These authors acknowledged that many other combinations of materials could also be candidates for Io's surface but, given the suite of materials they explored, this was the best combination of materials that fit the set of diverse data available at the time.

2.3.5 Late developments – setting the stage for *Voyager*

Despite the consensus around the evaporite hypothesis as the pre-*Voyager* paradigm, there were continuing developments prior to *Voyager* which were harbingers of the many changes in the paradigm which the *Voyager* results were about to establish. Several groups undertaking observations in the thermal-infrared reported that although Io emits too little radiation at 20 μm, it exhibits anomalously high infrared brightness temperatures in the 3–5-μm spectral region, implying the occurrence of events of very high temperatures on the surface (Morrison and Cruikshank, 1973; Hansen, 1975). Reports of episodes of high flux at various infrared wavelengths continued until the eve of the *Voyager* encounter (Witteborn *et al.*, 1979). (See Chapter 7 for further historical details.)

In continued studies of circum-Jovian space, Kupo *et al.* (1976) reported the first emission lines from the plasma torus when they detected the forbidden lines of singly ionized SII at 671.6 and 673.1 nm. Subsequently, additional lines of ionized S and O were observed from the ground, from the International Ultraviolet Explorer satellite, and from *Voyager*. Monochromatic images taken with filters isolating the plasma emission lines showed the torus in Io's orbit, with a tilt of some 9.6 degrees imposed by the inclination of Jupiter's magnetic equator to the satellite's orbital plane (Pilcher, 1980). Brown (1976) demonstrated the utility of the collisionally excited emissions in the plasma for determining the electron density, and the ion and electron temperatures in the torus. These observations added strong support to the spectroscopic argument that sulfur was a principal constituent of Io's surface. Any model which was to explain Io's surface surely had to include elemental sulfur as a major component or else go to great lengths to explain its absence.

There were further investigations into Io's surface composition that invoked elemental sulfur S_8 as the principal cause of an absorption feature at 400–500 nm. While the evidence for sulfur on Io's surface was quite strong, the spectrum of S_8 measured in the laboratory, even considering the effect of varying temperature and particle size, was not a convincing match to Io's spectral geometric albedo. The spectrum of sulfur increased far too sharply with wavelength from 400–500 nm to fit Io's spectrum well.

Nelson and Hapke (1978) measured Io's spectrum from 320–350 nm using a spectrometer which provided five times the resolution of the narrowband filter measurements which had previously constituted the best spectral data on Io. They found a previously unknown spectral absorption band beginning shortward of 330 nm (consistent with the OAO-2 report of a very low albedo at 280 nm by Caldwell (1975)). In addition, they called attention to the existence of many allotropic forms of elemental sulfur, of which the most common allotrope, cyclooctal sulfur S_8, is just one. They noted that other short chain allotropes and long chain polymers of sulfur, alone or in combination, would better match Io's spectrum in the near-ultraviolet, visible, and near-infrared spectral range. They noted furthermore that these other allotropes were easily formed by melting and quenching, or by irradiation, and once formed they were metastable at low temperatures. Nelson and Hapke (1978) suggested, "These allotropes of sulfur could be made naturally on Io by a number of processes. One way is by melting yellow sulfur as would be expected to occur in the vicinity of a volcanic fumarole or hot spring followed by sudden quenching to produce red sulfur."

Continued infrared telescope observations extended understanding of Io's spectrum deeper into the infrared. In 1978, a particularly distinctive set of absorption features between 3.3 and 4.07 μm, unique to Io, was reported by Cruikshank *et al.* (1978) and Pollack *et al.* (1978). Both groups compared their spectrum of Io to a wide range of eligible candidate materials, particularly those materials whose presence is consistent with the evaporite hypothesis, but were unable to find a suitable candidate to match the 4.07-μm feature. Elemental sulfur, regardless of allotropic form, does not have features at these wavelengths; instead it is highly reflective throughout this region. Therefore, a material which causes the strong 4.07-μm and related absorption features, if it could be identified, could, when combined with sulfur in one or more allotropic forms, explain most of Io's spectrum. However, laboratory spectra of a large suite of evaporite materials did not produce a match for Io's infrared spectrum.

An especially prescient dynamical study of Io appeared early in 1979, as *Voyager 1* was approaching the Jupiter system for its March fly-by. Peale *et al.* (1979) noted that while Io's eccentricity as an object in free orbit was quite small, its forced eccentricity due to the presence of the other Galilean satellites is quite large; large enough that extensive tidal heating would be expected. They concluded that Io's core could be molten and that it would have a crust that was quite thin. This tidal heating effect might explain the previous infrared observations of anomalously high temperature and episodic thermal outbursts. Peale *et al.* (1979) also noted, "... one might speculate that widespread surface volcanism would occur leading to extensive differentiation and outgassing." This conjecture based on dynamical calculations was the final and most compelling concept presaging what *Voyager* was about to find.

2.4 THE *VOYAGERS* ARRIVE AT JUPITER

2.4.1 Volcanoes on a distant world

While the evidence which led to the development of the evaporite hypothesis was accumulated at a measured pace on a timescale of decades, the *Voyagers* provided massive amounts of data in a highly compressed time frame. Thus, the previously existing models, which were developed over the course of a decade, were refined essentially overnight. New models were rapidly developed as diverse data sets arriving nearly simultaneously from the spacecraft were studied and integrated.

As *Voyager 1* approached the Jovian system, on-board particle detectors began to detect anomalously high concentrations of sulfur, sodium, and oxygen prior to the entry of the spacecraft into the magnetosphere. Krimigis *et al.* (1979), reported, "... it is probable that the sulfur, sodium and possibly oxygen originate at Io." This view was consistent with sputtering as a mechanism for removal of material from Io's surface. As *Voyager* approached Io itself, images of the surface revealed no impact craters whatsoever. This striking absence of impact craters stood in stark contrast to the

Figure 2.7. Io volcanoes: the discovery image. This figure shows two volcanoes. The image was the one in which Linda Morabito, a JPL navigation engineer, discovered the active volcanism. She was fitting the limb of Io against background field stars in order to refine *Voyager*'s trajectory, and noticed the plume on the edge of the image (from Morabito *et al.*, 1979).

surfaces of the Moon, Mercury, Mars and its moons, Phobos and Deimos, where telescopic and spacecraft images had revealed ancient, heavily cratered landscapes. Because there is no plausible mechanism that could shield Io from impacts, the youth of Io's surface and the recent covering of impact craters quickly after formation emerged as an inescapable conclusion.

The reason for Io's youthful surface became clear when *Voyager* images revealed towering plumes ejected from vents on the satellite's surface as stunning expressions of a profoundly active volcanic world (Figure 2.7, from Morabito *et al.*, 1979). And stunned indeed were planetary scientists, to a person. Active volcanism on Io stands as perhaps the most compelling finding of the *Voyager* fly-by of the Jovian system. In all, there were nine active plumes seen at the time of the *Voyager 1* fly-by (Strom *et al.*, 1979), and hot regions on Io's surface associated with the volcanoes were discovered (Hanel *et al.*, 1979). Previously undetected ionized species of sulfur and oxygen were found in the torridal ring of ionized material that orbits Jupiter at Io's approximate distance (Broadfoot *et al.*, 1979), as material sputtered from Io's surface is transported to the torus, where ultimately it escapes to the broader Jovian environment.

Images of Io taken at several wavelengths showed that the colors of the surface materials were consistent with allotropic forms of sulfur (Smith *et al.*, 1979). While allotropic sulfur was generally agreed to as one of Io's surface components, *Voyager* results provided important evidence for identification of the other principal material present, condensed sulfur dioxide. The *Voyager* infrared radiometer reported a significant presence of SO_2 gas measured against the background of the hot spot, the abundance was high enough to suggest that the gas was in equilibrium with material on the surface (Pearl *et al.*, 1979). The detection of SO_2 as a gas was the first evidence of a neutral atmosphere (though patchy in its distribution) on Io, and it caused several groups to measure the reflectance spectrum of SO_2 frost in the laboratory. These efforts quickly revealed that SO_2 was an excellent match for the previously unidentified absorptions in Io's infrared spectrum at 4.07 μm and shorter wavelengths (Fanale *et al.*, 1979; Smythe *et al.*, 1979). Hapke (1979) independently suggested that SO_2 frost might be present based on the spectral properties of the gas. Nash and Nelson (1978) reported that the 4.07-μm features could also be explained by SO_2 gas adsorbed on the other surface materials. SO_2, as a frost or as an adsorbate, was clearly the previously unidentified substance that, along with sulfur allotropes, covered the vast preponderance of Io's surface.

The distribution of the two main surface constituents to specific locales on Io's surface could not be established from *Voyager* images because the absorption features of condensed SO_2 lay beyond the wavelength limits of the spacecraft's cameras working in the visible region, and were too short for the operational spectral range of the infrared spectrometer. However, within a year of the fly-bys, Nash *et al.* (1980) had measured the reflection spectrum of SO_2 frost in the laboratory and found another band at 330 nm, where Nelson and Hapke (1978) had previously reported a feature from ground-based data. Nelson *et al.* (1980) using the International Ultraviolet Explorer spacecraft, which observed Io from Earth orbit, were able to confirm the existence of the 330-nm band and demonstrate that its strength correlates with Io's sub-Earth longitude in the same sense as does the 4.07-μm SO_2 feature reported by Cruikshank *et al.* (1978) and Pollack *et al.* (1978). Therefore, they concluded that the SO_2 frost was asymmetrically distributed in longitude on Io's surface with the frost being almost absent between Io longitudes 250–323° and most abundant between longitudes 72–137°. From features in Io's spectrum at wavelengths beyond the range of the *Voyager* cameras, they found the reflective regions on Io where the concentration of SO_2 is greatest. Continued observations of Io's infrared SO_2 bands by Howell *et al.* (1984) with ground-based telescopes demonstrated that the sulfur dioxide concentrations had not changed in position in the approximate 8 years since the feature was first observed (in November 1976) by Cruikshank *et al.* (1978). In a study summarizing the photometric results of the *Voyager* imaging system, Soderblom *et al.* (1980) concluded that the data were consistent with an Io surface composition consisting of mixtures of sulfur dioxide frost and allotropes of elemental sulfur.

2.4.2 Mountains of sulfur or silicate?

The tidal heating mechanism discovered by Peale *et al.* (1979), combined with *Voyager* confirmation that sulfur was ubiquitous on Io's surface, caused considerable re-appraisal of models of thermal evolution of planetary sized bodies. If Io had been subjected to the heating it currently experiences throughout its history, it surely would be the most evolved planetary body in the Solar System. Both the sulfur and SO_2 currently escaping from Io have molecular weight of 64, suggesting that volatiles of lower molecular weight (such as water, MW = 18) were lost long ago. Calculated resurfacing rates suggested that Io surface materials had been recycled many times over its existence (Johnson *et al.*, 1979). Thus, Io was analogous to a smelter that had been running for all of geologic time. While the post-*Voyager* consensus of a sulfur and SO_2 frost surface for Io took hold (see the review by Sill and Clark, 1982), the processes which led to that surface composition state were subject to intense discussion. This combination of knowledge and speculation framed the context for the development of the revised paradigm.

Sagan (1979) elaborated on the earlier suggestion that mixtures of sulfur allotropes could easily be produced in Io's thermal environment and might explain Io's coloration by noting that a very peculiar viscosity property of molten sulfur might create diagnostic landforms on Io's surface. Solid sulfur melts at ~392 K and, as heating continues, the viscosity decreases with increasing temperature until the melt reaches 432 K. Remarkably, above this temperature the viscosity of the melt *increases* by a factor of 10^4 as the principally S_8 cyclooctal ring breaks and long chain polymers of sulfur form. Sagan therefore suggested that much of Io's surface morphology could be explained by sulfur masses which formed volcanic edifices around the hot spots. He argued that the effluent from the sulfur volcanoes flowed down the slopes sluggishly at temperatures higher than 432 K and then, as the high-temperature sulfur crosses the viscosity threshold rapid outflows of sulfur would overflow and flood the downstream landscape with the short chain sulfur allotropes imparting the orange to yellow color characteristic of the lower temperature. The Sagan model suggested that the surface would be characterized by sulfur volcanoes with flanks covered with sulfur flows displaying the characteristic coloration and viscosity flow pattern of this material. An alternative model emerged concurrently with that of Sagan. Carr *et al.* (1979) argued, based on the properties of silicate magmas, that sulfur flows are unlikely to be the dominant form of Io volcanism. They suggested that while sulfur magmas might conceivably be produced from elemental sulfur separating from a sulfur-rich silicate magma, any flows thus produced could not explain major expressions of Io topography. They noted that the rugged topography of Io in many cases included nearly vertical sheer walls. While silicate materials have the strength to support such vertical relief, sulfur might not. Clow and Carr (1980) later reported that at the temperatures indicated by infrared observations of Io, sulfur would become ductile and therefore unable to support the steep walls seen in various places on the satellite. Sulfur could not be the foundation of Io's topography.

In broad outline, the immediate post-*Voyager* paradigm had been defined. Io's surface morphology was shaped principally by silicate material but sulfur and SO_2 coated the silicate surface, making these materials the only ones that were spectrally sensible from remote-sensing instruments.

2.4.3 Post-paradigm developments and modifications

The *Voyager* images gave the first views of Io at close range (Figure 2.8). The absence of craters established that Io has the youngest surface of all bodies so far viewed in the Solar System. Geologists have classified the surface units into three types: mountains, plains, and vent regions. The mountains have heights of up to 9 km and extend laterally for several hundreds of km; many mountains are volcanic but some are products of motion of the lithosphere. The plains are lacking in extensive vertical relief and resemble the regions of low-viscosity sulfur flows. The vent regions encompass

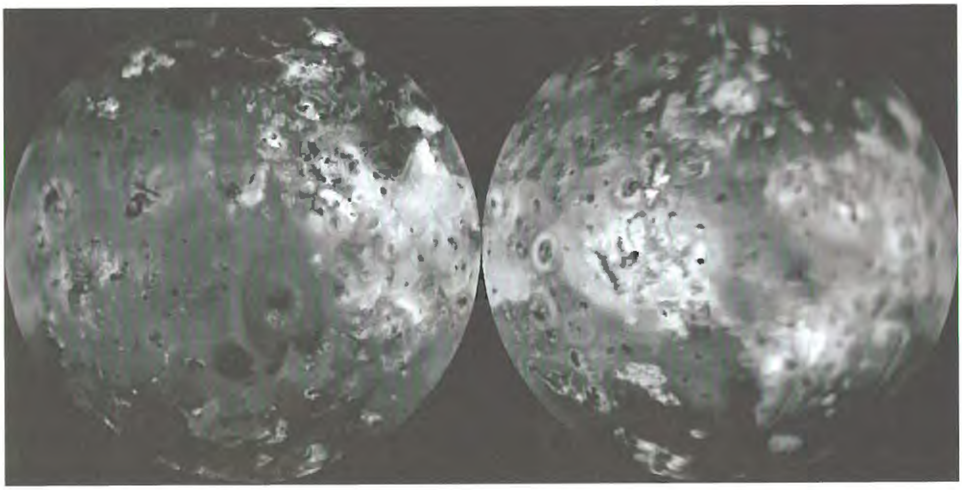


Figure 2.8. Mosaic of two hemispheres of Io from *Voyager* images. The *Voyager* images established that Io was devoid of impact craters and that Io's surface was the youngest in the Solar System. The detection of active volcanism caused a major shift in thinking regarding Io as a member of the outer Solar System of bodies (source: NASA Planetary Photojournal, image PIA00318.) (See also color section.)

crater-like depressions, dark circular features, and volcanic sources with radial flow patterns and bright halos. More detail is given in the review by Nash *et al.* (1986).

The role of silicate volcanism continued to be explored in the post-*Voyager* period using images from both spacecraft fly-bys, and continuing ground-based observations in the thermal-infrared. *Voyager 1* observed nine active plumes and 4 months later, *Voyager 2* observed eight of the nine as still active (Strom and Schneider, 1982). The images also permitted classification of the plumes into two categories. One group was comprised of three of the nine plumes observed by *Voyager 1*. This group was large, had distinct associated deposits consistent with the color of allotropic forms of sulfur, and appeared to be short-lived (a few days per eruption). The other group was characterized by plumes that were smaller in size, had distinct associated deposits which more closely resembled SO_2, and appeared to be continuous or very long-lived (McEwen and Soderblom, 1983).

2.4.4 The *Voyager* synthesis – sulfur or silicate volcanism?

The *Voyager* images of Io's volcanic surface provided morphological evidence which constrained the debate regarding the nature of the satellite's volcanism. While sulfur was one of the two materials which dominated Io's surface, the surface landform was silicate in nature. While sulfur could cover the outermost layers, elemental sulfur alone could not support the topography that the *Voyager* cameras observed. The underlying material was most likely silicate. A major question remained regarding silicate volcanism. Was the silicate volcanism occurring in the current epoch?

This question persisted as perhaps the major open issue following the first post-*Voyager* analyses. The answer to this question traces its origin to pre-*Voyager* observations in the thermal-infrared. Evidence for short episodes of high-temperature thermal activity had been presented in the literature (Section 2.2.2, see also Chapter 7) but was largely ignored because thermal anomalies of such large size were not expected on bodies as small as Io. However, the evidence continued to accumulate (Witteborn *et al.*, 1979). Between the two *Voyager* encounters Sinton (1980) reported a thermal outburst from his ground-based observations at a time when the Surt region on Io was visible from Earth. When *Voyager 2* flew by Io, it found that the Surt region had changed significantly during the time spanning the two fly-bys. Sinton *et al.* (1983) later summarized a series of observations noting eight outbursts, of which four could only be explained by temperatures having reached at least 700 K, consistent with the boiling point of sulfur in a vacuum (715 K).

Over the next few years various observers (Johnson *et al.*, 1984; Howell and McGinn, 1985) reported on continued monitoring efforts from ground-based observatories. Goguen and Sinton (1985) analyzed the polarization of infrared radiation from Io's hot spots and found that the emitter had an index of refraction that was closer to silicate than to elemental sulfur. Soon thereafter observers reported a thermal emission event that could only be interpreted as having originated from a flow that was 900 K, well above the boiling point of sulfur. They argued that this had to be a different material, perhaps giving evidence of silicate volcanism (Johnson *et al.*, 1988). Observations of high-temperature emissions continued over the next few years with still higher temperatures being reported. In their summary of this observation and reanalysis of earlier observations, Blaney *et al.* (1995) identified an event consistent with a flow temperature exceeding 1,200 K, and noted "... that the whole suite of Io's currently observed thermal anomalies was produced by multiple, high-eruptive-rate silicate flows within tbe past century". Thus, the case for silicate volcanism as the dominant mechanism at work in Io's hot crust was soundly established.

The post-*Voyager* synthesis gives us a view of Jupiter's strange moon in which silicate magmas, melted deep in Io by tidal heating, continue their slow recycling processes beneath a thin crust of sulfur and SO_2 frost. As they are ejected from Io's volcanic vents, sulfur and sulfur dioxide are continuously redistributed over the entirety of Io, burying older topography and creating new structures in a multicolored patchwork of flows, circles, and arcs. Here and there the bright pastel colors of Io are punctuated by a few molten, black silicate lakes distributed around the surface.

2.5 SUMMARY AND CONCLUSIONS

From the time of its discovery in 1610 to the mid-1800s, Io was a distinguished, but not a unique member of the set of four Galilean satellites, having utility as a means of determining the mass of Jupiter, finding geographic longitude of observers on Earth, and measuring the velocity of light. These merits, while not at all insignificant, are shared with the other three large moons, and do not capture the utterly unique characteristics of Io that began to emerge as the techniques of increasingly modern astronomy were applied to it toward the end of the 19th and throughout the 20th centuries. The pace of discovery accelerated through these times, as photometry, spectroscopy, radiometry, and ultimately close-up spacecraft scrutiny revealed the extraordinary properties and behavior of the most volcanically active body in the Solar System.

Since the first indications of Io's unusual behavior emerged in the early 1960s, the framework of our understanding of this unique world has been restructured several times, built on the most reliable available information and most informed speculation. This example is not uncommon in planetary science, astronomy, and indeed in all of science, but in the case of Io the journey has taken us to a quite unexpectedly compelling world whose secrets and their implications continue to emerge.

We began this chapter with the discoveries of Galileo, the scientist, and we end it with the discoveries of the *Voyager* spacecraft. In the next chapter, Jason Perry reviews the discoveries of *Galileo*, the spacecraft. The scientist contributed immeasurably to our understanding of the Solar System as a whole, and spacecraft from *Pioneer* to *Galileo* have revealed both the charms and the secrets of one of its most fascinating worlds.

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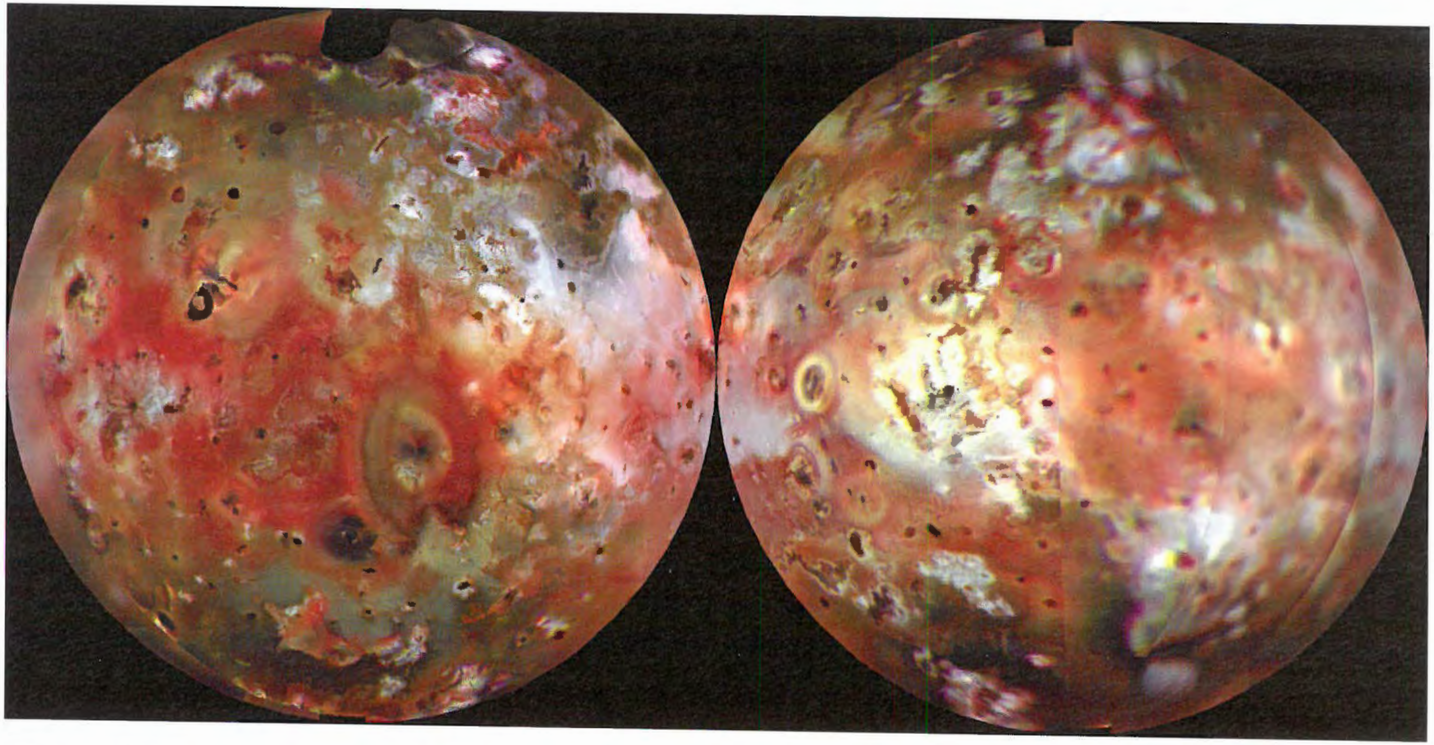

Figure 2.8. Mosaic of two hemispheres of Io from *Voyager* images. The *Voyager* images established that Io was devoid of impact craters and that Io's surface was the youngest in the Solar System. The detection of active volcanism caused a major shift in thinking regarding Io as a member of the outer Solar System of bodies. (Source: NASA Planetary Photojournal, image PIA00318.)