Introduction

Volcanism: *the manifestation at the surface of a planet or satellite of internal thermal processes through the emission at the surface of solid, liquid, or gaseous products.*

Peter Francis (1993), *Volcanoes: A Planetary Perspective*

Few geological phenomena inspire as much awe as a volcanic eruption. Eruptions are, quite frankly, extremely exciting to watch and experience. Could there then be any more exciting place to a volcanologist than the jovian moon Io (Plate 1), which has more active volcanoes per square kilometer than anywhere else in the Solar System? Io is the only body in the Solar System other than the Earth where current volcanic activity can be witnessed on such a wide scale. As a result of this high level of volcanic activity, Io has the most striking appearance of any planetary satellite.

The detection of an umbrella-shaped plume extending high above the surface of Io was the most spectacular discovery made by NASA's *Voyager* spacecraft during their encounters at Jupiter; in fact, it was one of the most important results from NASA's planetary exploration program. The discovery of active extraterrestrial volcanism meant that Earth was no longer the only planetary body where the surface was being reworked by volcanoes. With this exciting discovery a revolution in planetary sciences began, leaving behind the perception of planetary satellites as geologically dead worlds, where any dynamic process had been damped down into extinction over geologic time (billions of years).

The two *Voyager* spacecraft would continue through the Solar System on a grand tour of the gas-giant planets, passing Saturn, Uranus, and Neptune. More volcanic activity, this time cryovolcanic in nature, was discovered by *Voyager* on the neptunian moon Triton (Smith *et al.*, 1989; Kirk *et al.*, 1995). The *Cassini* spacecraft, which at the time of this writing was orbiting Saturn, has detected anomalies in the atmosphere of Titan that may indicate ongoing volcanic activity (Sotin *et al.*, 2005) and active volcanism on Enceladus (Porco *et al.*, 2006). These planetary satellites are active, dynamic worlds. This realization began at Io.

This book is divided into six sections. Section 1 (Chapters 1 to 3) deals chronologically with Io observations and discoveries, which began at the very dawn of telescope-based astronomy in the seventeenth century; covers the discoveries made by technological masterpieces – the two *Voyager* spacecraft; and examines other studies of Io after *Voyager* and up to the arrival of the *Galileo* spacecraft at Jupiter at the end of 1995.

Sections 2 and 3 provide essential background for understanding observations of volcanic activity. The dynamic nature of Io having been established, just why Io and Earth are so volcanically active today is examined in detail in Section 2. Chapter 4 summarizes current theories of formation and evolution of Earth and Io and the root causes of volcanism. Chapter 5 then describes the genesis, properties, and behavior of magmas and the effects of dissolved volatiles, common on Io, on magma behavior.

Section 3 covers how volcanoes on Io and Earth are studied using remote-sensing techniques and how mathematical models yield a quantitative understanding of volcanic activity. As noted by Peter Cattermole in his excellent book *Planetary Volcanism* (Cattermole, 1996), the exploration of volcanoes throughout the Solar System follows principles that are well known and fundamental to geology. For the specific case of understanding observations of volcanic activity from remote-sensing platforms, such investigations can be broken down into three stages.

The first stage consists of the acquisition of data, ideally at as high temporal, spatial, and spectral resolutions as possible. Visible-wavelength image data reveal volcanic plumes, lava flows, and surface morphology. Infrared data yield surface temperatures. Reflectance spectra are analyzed to reveal, or at least constrain, composition. Observations at shorter wavelengths, in the ultraviolet, detect molecular gas transitions. Accordingly, Chapter 6 describes the remote-sensing techniques available for studying Io's volcanism.

The second stage of investigation involves the formation of a theory, based on all available data, of the physical processes involved that might explain the observations. From theory, a mathematical expression of the physical process is often developed. Chapter 7 describes those models with a particular focus on understanding volcanism on Io.

The third stage of investigation consists of applying the models to data. To be an accurate representation of the process taking place, any model should be able to predict subsequent physical conditions. Once the accuracy of a model is established, it becomes a valuable tool for data interpretation. Chapter 8 describes how different volcanic eruption styles can be identified from measurements of thermal emission.

Section 4 (Chapters 9 to 14) examines *Galileo*'s discoveries and looks at volcanic activity at individual locations: a tour of the volcano bestiary. *Galileo* revealed many different styles of volcanic activity taking place on Io, both effusive and explosive in nature. As on Earth, differences in magma composition, gas content, and tectonic setting play a role in the surface expression of volcanic activity. Where possible, Section 4 looks at individual volcanic centers, examines what was seen by *Galileo*, and then quantifies the volcanic processes using the techniques in Section 3. Volcanism on Io produces features that are familiar to terrestrial volcanologists: lava flows, lava lakes and ponds, pyroclastic deposits, and interactions between hot lava and surface volatiles. Where possible, ionian eruptions are quantitatively compared with similar styles of activity on Earth.

On Io, we observe volcanic activity on a scale that would be quite catastrophic on Earth, as well as processes that may have been extinct on Earth for millions and, in some cases, billions of years. By watching how eruptions in the extreme ionian environment evolve, we gain insight into similiar terrestrial eruptions both today and in Earth's distant past. Resulting hypotheses and mathematical models, developed to explain extinct processes, can then be tested against new data of the process in action.

Every chapter in Section 4 highlights a different facet of Io's volcanism. Chapter 9 assesses the major discoveries made by *Galileo* and how the satellite had changed since *Voyager*. The next four chapters deal with very different expressions of volcanism at five locations:

- At Pele, an active, persistent lava lake;
- At Pillan and Tvashtar Paterae, rapidly emplaced lava fountains and voluminous flows;
- At Prometheus, an extensive insulated flow field emplaced over 16 years; and
- At Loki Patera, a quiescent, periodically overturning lava sea covering over 20 000 km^2.

These are mostly familiar scenarios to a volcanologist, seen in many locations on Earth, but on Io they are on a vastly different scale. In the case of Loki Patera, there is no terrestrial analogue of this size, and there may never have been.

Different analyses performed at each location highlight a different technique of interpreting data of volcanic processes. In all cases, spectral signature constrains, to some extent, the lava emplacement or exposure mechanism. At Pele, the steadiness of wavelength of peak thermal emission is an important clue to the nature of activity. At Pillan, the modeling of variability in discharge rate yields clues to the emplacement of large, voluminous flows on Earth and Mars. At Prometheus, modeling the variability of effusion rate yields a picture of crustal structure and magma supply from a magma chamber. The temperature distribution at Loki Patera, derived from fitting data with thermal emission models, reveals the mechanism by which the patera is being resurfaced.

Chapter 14 looks at other ionian volcanoes and eruptions that exhibit other interesting facets of volcanic activity.

Section 5 summarizes, in a global context, Io's geomorphology (Chapter 15), volcanic plumes (Chapter 16), and hot spots (Chapter 17), including assessment of the role played by volcanism as a medium for transporting heat on Earth and Io.

Section 6 takes a broad look at Io after the *Galileo* mission, assesses what has been learned, and identifies the important questions raised after *Galileo* (Chapter 18). The prospects for future observations of Io that may answer these questions are covered in Chapter 19.

This book includes two appendices. Appendix 1 contains the locations of volcanic hot spots identified on Io. Appendix 2 contains maps of Io showing the locations of all named features.

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Excerpt
More Information

Section 1

Io, 1610 to 1995: Galileo to *Galileo*

1

Io, 1610–1979

This chapter reviews the history of Io observations up to and including the *Voyager* encounters. The material in this chapter is drawn primarily from *Satellites of Jupiter* (Morrison, 1982) and *Satellites* (Burns and Matthews, 1986), both published by the University of Arizona Press, and *Time-Variable Phenomena in the Jovian System*, NASA Special Publication 494 (Belton *et al.*, 1989).

1.1 Io before *Voyager*

The study of Io dates from the very beginning of telescope-based astronomy. In his observation notes for January 7, 1610, Galileo Galilei wrote: "when I was viewing the heavenly bodies with a spyglass, Jupiter presented itself to me; and because I had prepared a very excellent instrument for myself I perceived that beside the planet there were three little stars, small indeed, but very bright." Subsequent observations revealed a fourth "little star."

Thus were discovered the Galilean satellites, named by Simon Marius (a contemporary of Galileo) Io, Europa, Ganymede, and Callisto. Subsequently, little attention was paid to the satellite system except as a means of measuring the speed of light (Roemer's method). Not until the nineteenth century did physical observations become important. In 1805, Laplace used the orbital resonant properties to estimate satellite masses. New refracting telescopes at Lick and Yerkes measured satellite sizes, and bulk densities were obtained.

The development of photographic and photoelectric techniques in the early twentieth century led to the determination of satellite light curves, proved that all four Galilean satellites were in Jupiter-synchronous rotation (Stebbins, 1927; Stebbins and Jacobson, 1928), and led to the discovery of prograde and retrograde groups of smaller outer jovian satellites. Since the latter half of the twentieth century, larger telescopes and modern techniques of photometry, spectro-photometry, and polarimetry have been used to determine colors, albedoes, and more accurate values of sizes and densities. Io was found to have the reddest surface in the Solar System (this work is summarized by Harris [1961]).

The occultation of a star by Io in 1971 yielded the first high-precision radius, 1818 km (Taylor *et al.*, 1971). Spectroscopy soon showed that water was a major component of the surface material of Ganymede and Europa (Pilcher *et al.*, 1972; Fink *et al.*, 1973) but was absent (down to the 1% level) on Io, already marked as being anomalous in the jovian system by its high albedo (0.6), red color, and post-eclipse brightening (first noticed by Binder and Cruikshank [1964]). In 1971, Sodium D line emission from Io was discovered (Brown, 1974) and a cloud of neutral sodium in the vicinity of Io was mapped (Trafton *et al.*, 1974; Trafton, 1975a), which led to the discovery of a potassium cloud (Trafton, 1975b). These features appeared to have their genesis on Io. The sputtering of material from the surface of Io by bombardment of charged particles trapped in the intense jovian magnetic field was proposed as the removal mechanism (Matson *et al.*, 1974).

The first spacecraft observations of the jovian system were made by *Pioneer 10* in 1973. The primary task of *Pioneer 10*, apart from proving the feasibility of deep-space missions, was the measurement of fields and particles in the spacecraft's environment. Particular attention was focused on the jovian magnetosphere, the most powerful planetary magnetosphere in the Solar System. Although few satellite measurements were made, improved values for satellite masses were calculated from analysis of *Pioneer*'s trajectory through the jovian system (Anderson *et al.*, 1974). With a more accurate radius determination of 1815 km (Davies, 1982), the bulk density of Io was calculated to be 3540 kg m^{-3}, very similar to that of the Moon and indicating a composition dominated by silicates. A radio occultation of the spacecraft revealed that Io had an ionosphere or possibly an extended atmosphere (Kliore *et al.*, 1974, 1975). *Pioneer 10* also detected an extended hydrogen cloud near the orbit of Io (Judge and Carlson, 1974) as well as a high-energy flux tube linking Io to Jupiter. This flux tube was later found to be a control on Jupiter's decametric radio emission (Dessler and Hill, 1979; Desch, 1980). In December, 1974, *Pioneer 11* obtained a low-spatial-resolution image of Io from high above the north pole, showing that the northern hemisphere had some low-albedo areas.

In the wake of *Pioneer*, considerable attention was focused on the spectrum of Io. Wamsteker *et al.* (1974) were among those who noted a strong similarity between the spectrum of Io and that of sulphur, and it was proposed that sulphur was abundant on the surface of Io. Ionized sulphur emission from Io was discovered by Kupo *et al.* (1976). Spectral observations and laboratory work refined the Io spectrum and revealed a strong ultraviolet absorption feature, although the cause of this feature remained unknown until *Voyager* and laboratory work identified sulphur dioxide on the surface of Io.

Pre-*Voyager* spectral work is reviewed by Johnson and Pilcher (1977), and the reader is also directed to Cruikshank *et al.* (1977), Nash and Fanale (1977), Cruikshank *et al.* (1978), Pollack *et al.* (1978), and Fink *et al.* (1978).

The strong absorption feature in Io's spectrum at 4.1 microns (μm), observed by Cruikshank *et al.* (1978) and Pollack *et al.* (1978), was identified from laboratory studies as sulphur dioxide in the form of a frost or adsorbate (Fanale *et al.*, 1979; Smythe *et al.*, 1979). Again, no water absorption bands were seen in telescope observations, demonstrating that Io's surface was water-ice-free and therefore very different from the water-rich surfaces of the other Galilean satellites.

1.2 Prediction of volcanic activity

Even prior to *Voyager*, it was evident from ground-based instruments that Io had unusual far-infrared photometry and radiometry, with higher brightness temperatures at 10 μm than at 20 μm (Morrison *et al.*, 1972) and unusual thermal inertia as Io emerged from eclipse (e.g., Hansen, 1973; Morrison and Cruikshank, 1973). These observations were difficult to interpret in the context of Io's being a dead, inactive world.

Just before the *Voyager 1* encounter with Io in March, 1979, a notable discovery was made. Witteborn *et al.* (1979) announced that an intense, temporary brightening at 2 to 5 μm in the infrared had been observed, which they explained as an isolated surface area at a temperature of ≈600 K (on a planet where the peak daytime temperature is ≈130 K). Another hint of Io's dynamic nature came from Nelson and Hapke (1978), who suggested fumarolic activity as a possible mechanism for producing short-chain sulphur allotropes on Io's surface to explain features in Io's spectrum.

Only a few days before *Voyager 1* observed Io (and demonstrating exquisite timing), Peale *et al.* (1979) published an epochal paper on the heating of Io by tidal forces, in which they predicted "widespread and recurrent volcanism."

Voyager was to prove their theory spectacularly correct.

1.3 *Voyager* to Jupiter

Before the spinning *Pioneer 10* spacecraft had even reached Jupiter, development had already started on its successor. *Voyager* was based on the more sophisticated three-axis-stabilized *Mariner* spacecraft developed by NASA's Jet Propulsion Laboratory (JPL) in Pasadena, California. At launch, *Voyager* was eight times the weight of *Pioneer 10*, requiring NASA's most powerful available booster, the Titan IIIE, plus a Centaur upper stage to send it on its way to Jupiter. The *Voyager* project was developed as a multi-planet investigation of at least ten years' duration, for visiting

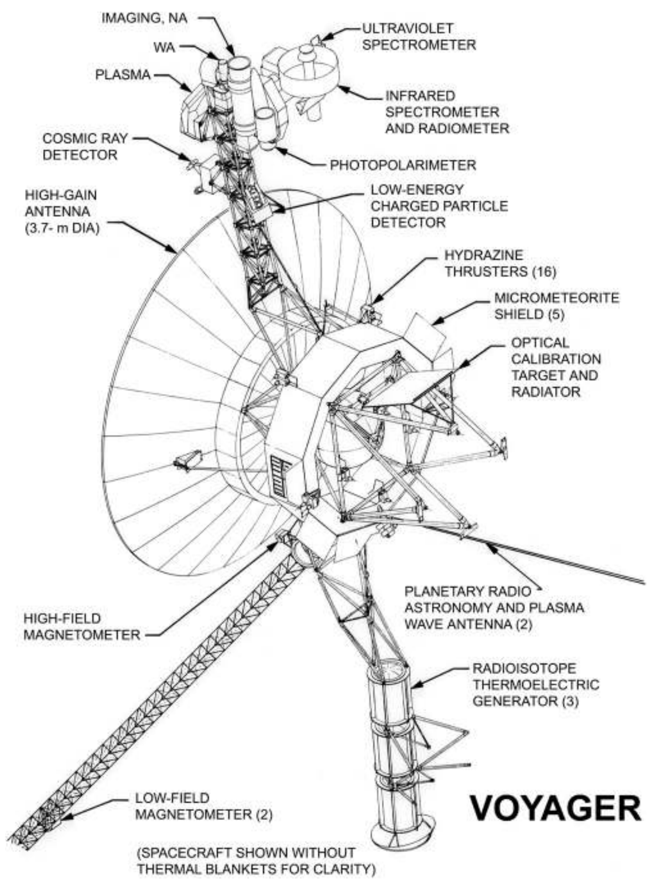

Figure 1.1 The fully deployed *Voyager* spacecraft. Courtesy of NASA.

Jupiter and Saturn and, hopefully, Uranus and Neptune as well: the long cherished "Grand Tour."

Each *Voyager* spacecraft (Figure 1.1) weighed 815 kg in full deployment and carried three classes of instruments designed to collect information about the physical and chemical natures and radiation environments of 15 or more planetary bodies. The first group of instruments was mounted on a stabilized scan platform, a feature absent from the *Pioneer* design, which was essential to compensate for the speed of the spacecraft as it passed close to planets and their satellites. These instruments were two television cameras (imaging sub-system [ISS], not to be confused with the instrument with the same acronym on *Cassini*), one wide- and the other, narrow-angle; an infrared radiometer interferometer and spectrometer (IRIS); an ultra-violet spectrometer (UVS) to assess gas composition; and a photo-polarimeter (PPS) to measure molecular hydrogen, methane, and ammonia in planetary atmospheres.

Table 1.1 Voyager *Galilean satellite encounters*

Satellite	Closest approach (km)	Best resolution (km/line pair)
Voyager 1		
Io	20 570	1[a]
Europa	733 800	33
Ganymede	114 700	2
Callisto	126 400	2
Voyager 2		
Io	1 129 900	20
Europa	205 700	4
Ganymede	62 100	1
Callisto	214 900	4

From Stone and Lane (1979a, 1979b).
[a] Best Io resolution limited by image smear.

Another set of instruments measured the strength of magnetic fields and the energies of charged particles: a plasma detector, a low-energy particle detector, two solid-state cosmic ray telescopes, and four magnetometers.

Finally, two 10-m antennas were used for radio astronomy experiments. The radio communications system was also used to sound planetary atmospheres and ionospheres by transmitting through them. All data were transmitted back to Earth at 23 W (watts) of power at rates up to 115.2 kB/s, to be received by stations of the Deep Space Network. Data were assembled, collated, and transmitted to JPL.

Voyager 1 was launched on September 5, 1977, 16 days after *Voyager 2* (which was on a slower trajectory), and began substantive monitoring of the jovian system on January 6, 1979. Its closest approach to Jupiter was at a distance of 348 890 km on March 5, 1979. *Voyager 2* arrived at Jupiter 18 weeks later and encountered Jupiter at a perijove of 721 670 km on July 9, 1979 (Stone and Lane, 1979a, 1979b).

At Jupiter, the two *Voyagers* were on complementary trajectories. *Voyager 1* made close fly-bys of Io, Ganymede, and Callisto after perijove, making a south polar passage by Io (which would confirm the existence of the flux tube linking Io to Jupiter). *Voyager 2* made close approaches to Europa, Ganymede, and Callisto, but not Io (see Table 1.1), before perijove on a trajectory that would swing the spacecraft onto a course not only toward Saturn, but Uranus and Neptune as well.

Voyager 1 passed by Io at a periapsis of 20 570 km (Table 1.1) and obtained images of moderate to high resolution (0.5–5 km/line pair) covering ≈40% of the surface (see Strom *et al.* [1981]). Table 1.2 shows the number of images taken as a function of resolution. The highest resolution images taken by *Voyager 1* were of the southern hemisphere of Io. *Voyager 2* took only low-spatial-resolution images of Io.