Driven by tidal heating, Io’s extreme volcanism has created a young, impact crater–free surface dominated by hundreds of active volcanic centres. From these volcanoes erupt voluminous, low-viscosity, high-temperature silicate lavas. Volcanic plumes, from venting gas and mobilised surface ices (primarily SO₂ and S), contribute to Io’s thin atmosphere. Away from volcanoes, SO₂ ice on the surface alternately sublimes during the daytime and condenses during eclipses and at night, resulting in a strong day/night atmospheric dichotomy. Sunlight and radiation bombardment at high altitude breaks the gas molecules apart, leading to the formation of SO, O, O₂, S, K, Na, and Cl. These atoms reside as both neutral and charged particles in clouds that are found along Io’s orbit around Jupiter.

Keywords: Jupiter; Io; volcanism; atmosphere

INTRODUCTION

Io’s widespread volcanic activity and its atmosphere are inextricably linked (Figs. 1 and 2). Volcanoes erupt large volumes of lava, generating plumes (Fig. 2) rich in gases that have escaped from the lava. Lava flows also mobilise volatiles frozen on the surface. The resulting plumes, which entrain silicate dust and lava emplaced on Io’s surface, therefore provide opportunities to establish the lava composition and constrain Io’s interior state via remote sensing. Io’s volcanoes contribute to an atmosphere that varies in structure, nearly collapsing during Io eclipses (in the shadow of Jupiter) and at night. This atmosphere provides a ready source of material for Io’s giant plasma torus of charged particles (ions and electrons), which stretches around Io’s orbit of Jupiter. Here, we examine both Io’s volcanoes and its atmosphere.

IO’S VOLCANOES

Io is a volcanic wonderland. It was the Voyager spacecraft—the most successful planetary explorers NASA has ever launched—that revealed why Io was so different to every other moon in the Solar System. Voyager changed the paradigm of what was known and believed about outer Solar System satellites. Through telescopes, Io had always presented a different aspect to the other moons orbiting Jupiter. It was not covered in water ice. Uniquely, there were rare, transient changes in its infrared brightness. Sulphurous compounds were identified in infrared spectra. Peale et al. (1979) proposed that Io could be volcanically active as the result of tidal heating arising from the 4:2:1 orbital resonance between Io, Europa, and Ganymede.

They published their theory just in time for the first Voyager encounter to spectacularly confirm it by imaging volcanic plumes rising tens to hundreds of kilometres above the surface (Morabito et al. 1979). The infrared brightenings observed from Earth were the result of powerful, voluminous volcanic eruptions. Voyager revealed a colourful surface devoid of obvious impact craters. The prodigious amount of volcanic activity has erased all impact craters larger than a few kilometres in diameter. Such rapid resurfacing leads to compression in the lithosphere as old layers are buried under new layers. Stresses are relieved by faulting and tilting of crustal blocks, forming mountains, some over 17 km high. Temperatures and surface colours derived from Voyager instruments suggested that Io’s volcanism was dominated by relatively low-temperature sulphurous material. Subsequent ground-based telescope observations revealed that at least some eruptions were silicate in nature (Veeder et al. 1994). Subsequently, data from the Galileo spacecraft between 1996 and 2001 showed that most volcanic eruptions on Io are dominated by silicate lavas, as is volcanism on Earth. The open question now is: what kind of silicates? Are Io’s lavas basaltic (like those of Hawai‘i)? Or are they higher-temperature, lower-viscosity, magnesium-rich ultramafic lavas that were once widespread on Earth? Ultramafic lavas would suggest a high degree of mantle melting. Or could both be present, reflecting dichotomies in internal heating? The answers to these questions are key to understanding the evolution, interior state, and composition of Io, and ultimately how the tidal resonance that drives activity on Io—and to a lesser but possibly significant extent within Europa—is evolving. Io is the best place in the Solar System to understand how tidal heating works.

Distribution of Volcanic Activity

Volcanism is the main mechanism by which heat is transferred from Io’s interior. Over half of Io’s observed thermal emission of 102 TW (Veeder et al. 1994) emanates from over 250 volcanic centres (Fig. 3), yet these areas cover only about 2% of Io’s surface. The manner of heat transport to the surface of the remaining heat flow, and its distribution, is unknown. This is important, as deep-mantle tidal heating should result in enhanced heat flow at Io’s poles, whereas shallower asthenospheric heating should result in enhanced surface heat flow at lower latitudes and focussed at specific longitudes (Ross et al. 1990). Io has anomalously warm poles (Spencer et al. 2000), but detailed temperature
mapping of the polar regions has not been possible because \textit{Galileo} operated in the equatorial plane. The overall compressional tectonic regime leads to local extension, and resulting faulting can provide pathways for rising magma. The ascent of deep-origin, possibly ultramafic, lavas often creates transient, powerful, voluminous eruptions with lava fountaining from multi-kilometre-long fissures. Other eruptions, many within caldera-like features called paterae, are smaller and persistent, often exhibiting significant variability that suggests storage in near-surface magma chambers. Tall volcanic plumes are driven by volatiles escaping from ascending magma and from the mobilisation of frozen sulphurous surface material. The lithosphere is at least 30 km thick and underlain by a partially molten upper mantle of silicate composition with a melt fraction of likely ≥10%. Sulphur dioxide (SO$_2$) ice on the surface alternately sublimes during the day and condenses during eclipses and at night. Higher altitude photochemistry breaks gas molecules apart to form SO, O, O$_2$, K, Na, and Cl. The atoms likely reside in a neutral cloud or an extended corona before being ionised and swept up into Io’s plasma torus.

\textbf{Styles of Volcanic Activity: Io as a Volcanic Laboratory}

\textit{Voyager} and \textit{Galileo} revealed a surface with a diverse array of volcanic features, dominated by extensive lava flows and caldera-like depressions called paterae. Many paterae are floored with silicate lavas. There are a few shield volcanoes (volcanoes shaped like shields, with gentle slopes). Io’s volcanoes dwarf their terrestrial contemporaries. The few persistent terrestrial lava lakes in existence are typically of order 100 m or so in diameter (Nyiragongo, in the Democratic Republic of Congo, is currently the largest active lava lake on Earth at about 300 m in diameter). On Io, Loki Patera, almost certainly a vast lava lake (or, perhaps more appropriately, a lava “sea”), is 180 km across, with an active area of over 21,500 km$^2$ (Veeder et al. 2012). The Pele lava lake is 38 km across.

Regarding lava flows, while the 2018 Leilani Estates eruption of Kilauea, Hawai‘i, erupted ~1 km$^3$ of lava, an eruption at Pillan on Io in 1997 erupted some 56 km$^3$ of lava and pyroclastic material (Keszthelyi et al. 2001), mostly in lava flows approximately 10 m thick. The first such measurement of an active, extraterrestrial lava flow, this thickness is akin to that of individual terrestrial flood basalt units. The >100-km-long lava flow field at Prometheus was largely emplaced in the 17 years between the \textit{Voyager} and \textit{Galileo} observations. Amirani’s lava flows are more than 300 km long. Some lava flow fields on Io cover over 500,000 km$^2$ (Veeder et al. 2012).

The morphology of the lava flows and volcanic structures suggest low-silica magmas. Temperature measurements from \textit{Galileo} data indicate lava eruption temperatures in excess of 1400 K, typical of basalt (McEwen et al. 1998), with some estimates in excess of 1600 K, suggestive of ultramafic compositions (e.g., McEwen et al. 1998; Davies et al. 2001). Definitive measurements of lava eruption temperatures, or spectral determinations of composition, have not been possible with existing data.
Io's most powerful "outburst" eruptions (the cause of the mysterious infrared brightenings in pre-Voyager telescope observations) are now known to be caused in some cases by lava fountains emanating from long fissures (Davies 2007). With peak thermal emissions exceeding 10s of TW, peak effusion rate estimates are in the range $10^5$ – $10^6$ m$^3$·s$^{-1}$ (Davies 2007; de Pater et al. 2014). These discharge rates are similar to those proposed for ancient and voluminous lava flows on terrestrial (i.e., rocky) planets and on the Moon. Io therefore presents an active volcanic laboratory for studying and revealing insights into eruption processes that helped shape the surfaces of the Earth, the Moon, Mars, Mercury, and Venus in their distant pasts.

It is possible to constrain the style of volcanic activity—the manner in which lava is erupted and emplaced—by studying the magnitude and evolution of the eruption's infrared thermal emission spectrum (Davies et al. 2010). The evolution of thermal spectra can be grouped by comparing the 2.5-μm spectral radiance ratios and radiant flux densities. For example, violent eruption styles expose more hot lava and have high 2.5-μm ratios and radiant flux densities, whereas more quiescent eruptions produce cooler, crusted-over lava that radiates more heat at 5 μm. Identifying the eruption style allows appropriate models to be applied to determine the discharge rate and constrain the lava eruption temperature.

Style of activity is only one facet of Io's volcanism. The thermal emission spectrum of an eruption is inextricably linked to the physical mechanisms of lava eruption, which in turn dictate the type or absence of plumes, and thus the atmospheric contribution of a given eruption. These other facets are discussed next.

**Io's Volcanic Plumes**

The first indication of Io's active volcanism was the discovery of volcanic plumes in Voyager images. These plumes are important contributors to Io's atmosphere. They contain entrained silicate and sulphurous materials and an inventory of volcanic gases that have exsolved from the magma as it rises to the surface.

Based on Voyager images, McEwen and Soderblom (1983) suggested two main plume classes: "Pele-type" plumes and "Prometheus-type" plumes. Pele-type plumes have been directly observed at a small number of locations, including Pele and Tvashtar Paterae. These plumes rise up several hundreds of kilometres (~350 km at Tvashtar Paterae and ~420 km at Pele) (Fig. 2) and are prominent in ultra-
violet observations. The Pele plume, emanating from a lava lake, is often difficult to observe directly but its presence is clear from a persistent, extensive (over 1200-km-diameter) red ejecta deposit (Fig. 2B). The other plumes of this class are sporadic, short-lived, and typically located at high latitudes, and, in the case of the Tvashtar Paterae plume observed by the New Horizons spacecraft, exhibit a symmetric, shield-like shape that lacks a clearly visible central column.

Prometheus-type plumes are more common, more persistent, and smaller (~100 km high) than Pele-type plumes, exhibiting a characteristic fountain- or umbrella-shaped morphology with a dense central column (Fig. 2A). These plumes are preferentially located at lower latitudes and often contain higher column abundances of gas and dust than Pele-type plumes.

Not all plumes fit the above mentioned bi-modal classification. For example, the plumes observed by Voyager emanating from Loki (lava flows located to the north of Loki Patera), appeared at first to be a hybrid class, but are now thought to be large Prometheus-type plumes.

Additionally, the 1997 Pillan eruption left a large, irregular (400-km-wide) black, silicate-rich pyroclastic deposit, surrounded by a white (likely SO₂-rich) aureole, on Io’s surface that temporarily obscured part of the Pele plume deposit (Fig. 2C).

A distinct subset of the Pele-type plumes is pure SO₂ gas-phase plumes generated by the thermal interaction between a buried SO₂ deposit and a silicate intrusion, the result being a hard-to-image “stealth” plume (Johnson et al. 1995) (Fig. 1). Recent ground-based observations (de Pater et al. 2020) that show areas of enhanced SO₂ remote from known volcanoes suggest that these may be stealth plumes.

Finally, plume-like emissions can also result from the relatively quiescent escape of small amounts of volatiles from recently emplaced lava and from sub-surface interactions between buried volatiles and silicate intrusions, often manifesting as small white streaks emanating from faults and the bases of scarps.

**Plume Generation Mechanisms and Implications**

The appearance of Io’s plumes and plume deposits, and the temporal evolution of both, reflect the different volcanic processes generating the plume types (Figs. 1 and 2). The large, red plume deposits seen at Pele and at other locations (for example, at Surt and Aten between Voyager encounters) are driven by primary volatiles degassing from deep-sourced silicate magma as it nears the surface. Rapid exsolution leads to explosive activity and high (>1 km·s⁻¹) eruption velocities. Telescope observations show these plumes are rich in short-chain sulphur allotropes, primarily S₂, that polymerise to S₃ and S₄. However, as these allotropes soon revert to yellow cyclo-octal S₈ under Io surface conditions, the persistence of the Pele plume (and therefore the lava lake) is evidenced by the continued presence of the red plume deposit.

Prometheus-type plumes are generated by the thermal interactions between silicate lava flows and surface ice deposits. The magma may be stored close to the surface, and is volatile-poor. These plumes are rich in dust and SO₂, and leave annular yellow and white/grey deposits of primarily SO₂. The most striking example of this is at Prometheus, where, over 17 years, the centre of the annular deposits moved westward, keeping pace with the emplacement of new lava, and thus revealing the plume generation mechanism. At Prometheus, lava moves 100 km from the vent, likely through lava tubes, before erupting onto the surface. Jets of SO₂ emanate from the distal margins of the lava flow and combine into a coherent plume. Denser, darker areas in the plume suggest more dust-rich jets, containing more entrained rocky material. At the lava flow source vent, a small red deposit indicates that some primary sulphur volatiles are degassing from the lava on eruption. The remobilisation of surface ices was the likely genesis of the two Voyager-era Loki plumes, and may have played a role in the emplacement of the 1997 Pillan deposit.

**IO’S ATMOSPHERE**

Io’s SO₂-dominated atmosphere has a surface pressure on the order of 1–10 nbar, approximately one billionth of Earth’s atmospheric pressure at sea level. The density and temperature of the atmosphere vary considerably with time-of-day, latitude, surface frost abundance, and volcanic activity. The ultimate source of SO₂ is volcanic outgassing, although it is not clear to what extent volcanoes contribute directly to the atmosphere, and to what extent the atmosphere is maintained by sublimation of SO₂ frost.
Since the first detection of gaseous SO₂ at 7.3 μm over the Loki volcanic centre in 1979 (Pearl et al. 1979), Io’s atmosphere has been extensively observed by both Earth- and space-based telescopes. While ground-based telescopes and telescopes in Earth orbit only provide information on the illuminated day-side atmosphere, and thus offer no information on atmospheric variations with time of day, they can observe Io right before, during, and after Jupiter eclipse, providing key observations for separating the volcanic contributions from the sublimation-driven contributions.

**Diurnal Cycle**

Io’s atmosphere, which is permanently detectable on the moon’s day-side (covering typically 50%–70% of the Sun-exposed surface), drops rapidly as Io enters eclipse (Tsang et al. 2016). The observed exponential decrease in atmospheric SO₂ flux density in the first few minutes after Io enters Jupiter’s shadow has been interpreted as a partial collapse of the SO₂ atmosphere onto the strongly cooled surface, and supports the current understanding of a primarily sublimation-controlled day-side atmosphere. In contrast to SO₂, non-condensible gases in the atmosphere (i.e., gases that do not freeze out, e.g., O₂, possibly SO) might “survive” Jupiter eclipse, changing the atmosphere’s composition drastically from an SO₂-dominated atmosphere to a non-condensible gas-dominated atmosphere. Non-condensible gases could also buffer, or even completely prevent, atmospheric collapse, though observations have shown this effect to be small. As Io re-emerges from eclipse, the atmosphere is strongly diminished. As described above, interactions between hot silicates, sulphur, and SO₂ produce a variety of plumes with different characteristic pressures, temperatures, sizes, and compositions. At Prometheus, visible in the centre of Figure 2A, the column density is 1.8 × 10¹³ cm⁻² (Jessup et al. 2004) while the vertical column densities in the Pele and Tvashtar Paterae plumes are ~4 × 10¹⁶ cm⁻² (McGrath et al. 2000; Spencer et al. 2000; Jessup and Spencer 2016).

**Atmospheric Composition**

Observations of Io’s atmosphere provide independent data that have been compared to thermal and visible observations of surface volcanism and plumes. SO₂, the most important volcanic gas present on Io (and a major constituent of volcanic gas emissions on Earth) makes up ~90% of Io’s surface pressure. SO₂ can dissociate into SO, S, O, and O₂, making these species also likely components of Io’s atmosphere. In fact, three of these four species have been observed in Io’s atmosphere by the **Hubble Space Telescope**, the **International Ultraviolet Explorer**, and ground-based telescopes; only O₂ is yet to be identified. The S and S₂ abundances in the plumes are of particular interest because they can constrain the likely formation mechanisms of the plumes, that is, high S and/or S₂ abundances indicate primary volcanic sources (e.g., Pele), while low S and/or S₂ abundances indicate secondary mobilisation of SO₂-rich surface ice (e.g., Prometheus).

Besides SO₂-related compounds, non-SO₂-related minor species have been detected in Io’s atmosphere, most notably NaCl and KCl (e.g., de Pater et al. 2020). Interestingly, the locations at which NaCl and KCl were observed, Isum and Uigen Paterae, did not produce simultaneous SO or SO₂ emissions, nor have plumes been observed there since. If NaCl and KCl are sourced by volcanism, which is supported by the observations, their spatial non-colocation with SO and SO₂ indicates differences in the magma melt composition at volcanic sites and/or access to different sub-surface reservoirs.

**Neutral Cloud and Plasma Torus**

Neutral S, O, Na, and K atoms that are ejected from Io’s atmosphere form a vast neutral cloud of several Io radii that surrounds and accompanies Io in its orbit around Jupiter. The net loss to the neutral cloud ranges from 250 to 3000 kg s⁻¹. Sodium, which is very efficient at resonant scattering of sunlight and therefore easy to detect (with emissions being 30 times brighter than those for potassium, for example), has been observed in Io’s neutral cloud on several occasions since first being detected in 1974 (Brown 1974). Direct volcanic ejection was shown by **Hisaki** spacecraft observations to at least double the O number density in the neutral cloud during a 90-day-long period of enhanced volcanic activity in spring 2015 (Koga et al. 2019). Particles are lost from the neutral torus through electron-impact ionisation and charge exchange, and become trapped in Jupiter’s magnetic field. These ions form the Io plasma torus, a “doughnut” of oxygen and sulphur ions of various charge states, with additional sodium (~10%), chlorine (~1%), and carbon (~1%) ions, plus electrons, that co-rotates with Jupiter’s magnetosphere. The plasma torus is dominated by O⁺, with observed abundances (~26%–40% of the electron density) requiring a neutral source with O/S mixing ratios of ~2–4. The lower mixing ratio value is compatible with an SO₂ origin (Delamere and Bagenal 2003). It is estimated that, through ion pick-up, Io adds upward of one ton s⁻¹ of plasma mass to Jupiter’s magnetosphere, making Io the main source of plasma in the magnetosphere.
OPEN QUESTIONS AND THE WAY FORWARD

Answering the outstanding questions about Io's volcanism and the role of tidal heating at Io requires constraining the interior state of the moon. One way to determine the composition of the erupting lava is to measure its eruption temperature. Doing that requires identifying eruption styles—lava fountains, roaring lava lakes, and lava tube skylights, for example—where the molten lava is newly exposed and at, or very close to, eruption temperature, and these hot areas can be isolated from surrounding areas at lower temperatures. Additionally, unsaturated, multi-wavelength observations have to be obtained fast enough that the cooling of the newly exposed lavas does not lead to high uncertainties in the derived temperatures, a major problem with temperature derivations from Galileo data. Lava composition can also be determined by identifying composition-dependent spectral features in the thermal infrared between 7 and 10 μm, at expanses of newly emplaced lava (abundant on Io) not yet covered by sulphurous plume fallout (Veeder et al. 2012).

Yet, even though we have a preliminary understanding of Io's atmosphere today, many questions remain unanswered, some of which are summarised here.

- Volcanoes clearly have a substantial impact on Io's atmosphere. But to what degree do they directly support Io's atmosphere; how do they influence the atmospheric dynamics; how do they interact with the bulk atmosphere; how do they alter the surface of Io; and how significant are they to Io's resurfacing? Millimetre and infrared data of eclipse ingress and egress, and high-latitude observations coupled with atmospheric modelling, would help answering these questions.

- What other species are present in both Io's plumes and bulk atmosphere, and what do they teach us about Io's surface and interior?

- Why are NaCl and KCl not collocated with SO 2 and SO enhancements or plume activity? Observations of NaCl and KCl at new sites would show if these species really are not collocated with SO 2, SO, and plume activity, and would help us understand their origin.

- What is the full range of Io's plume types and what is their global distribution, frequency, and duration? A global inventory of surface volcanism and volcanic plume activity has so far proved difficult, even with Jupiter-orbiting spacecraft.

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REFERENCES


