Astrophysics and Space Science Library 468

Rosaly M. C. Lopes
Katherine de Kleer
James Tuttle Keane *Editors*

Io: A New View of Jupiter's Moon

Second Edition

Springer

Astrophysics and Space Science Library

Volume 468

Series Editor
Steven N. Shore, Dipartimento di Fisica "Enrico Fermi", Università di Pisa, Pisa, Italy

The Astrophysics and Space Science Library is a series of high-level monographs and edited volumes covering a broad range of subjects in Astrophysics, Astronomy, Cosmology, and Space Science. The authors are distinguished specialists with international reputations in their fields of expertise. Each title is carefully supervised and aims to provide an in-depth understanding by offering detailed background and the results of state-of-the-art research. The subjects are placed in the broader context of related disciplines such as Engineering, Computer Science, Environmental Science, and Nuclear and Particle Physics. The ASSL series offers a reliable resource for scientific professional researchers and advanced graduate students.

Rosaly M. C. Lopes • Katherine de Kleer •
James Tuttle Keane
Editors

Io: A New View of Jupiter's Moon

Second Edition

Springer

Editors
Rosaly M. C. Lopes
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA, USA

Katherine de Kleer
California Institute of Technology
Pasadena, CA, USA

James Tuttle Keane
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA, USA

ISSN 0067-0057 ISSN 2214-7985 (electronic)
Astrophysics and Space Science Library
ISBN 978-3-031-25669-1 ISBN 978-3-031-25670-7 (eBook)
https://doi.org/10.1007/978-3-031-25670-7

Previous edition originally published in the series: “Springer Praxis Books in Astronomy and Planetary Sciences” with the title: “Io After Galileo - A New View of Jupiter’s Volcanic Moon” under: Lopes, R. M. C., Spencer, J. R.

© The Editor(s) (if applicable) and The Author(s), under exclusive license to Springer Nature Switzerland AG 2007, 2023, corrected publication 2024
This work is subject to copyright. All rights are solely and exclusively licensed by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publisher, the authors, and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Cover illustration: A montage of New Horizons images of Jupiter and its volcanic moon Io, taken during the spacecraft’s Jupiter flyby in early 2007. *Credit: NASA/JHU/APL.* https://www.nasa.gov/mission_pages/newhorizons/news/nh_jupiter_oct09.html

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Contents

Contributors

Fran Bagenal Laboratory for Atmospheric & Space Physics, University of Colorado, Boulder, CO, USA

A. C. Barr Planetary Science Institute, Tucson, AZ, USA

C. J. Bierson Arizona State University, Phoenix, AZ, USA

R. Brasser Origins Research Institute, Research Centre for Astronomy and Earth Sciences, Budapest, Hungary

Katherine de Kleer California Institute of Technology, Pasadena, CA, USA

I. de Pater Department of Astronomy, University of California, Berkeley, CA, USA

V. Dobos Kapteyn Astronomical Institute, University of Groningen, Groningen, The Netherlands
MTA-ELTE Exoplanet Research Group, Szombathely, Hungary

Vincent Dols Laboratory for Atmospheric & Space Physics, University of Colorado, Boulder, CO, USA

D. Goldstein Department of Aerospace Engineering, University of Texas at Austin, Austin, TX, USA

Amanda F. Haapala Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA

James Tuttle Keane Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

Laszlo P. Keszthelyi U.S. Geological Survey, Astrogeology Science Center, Flagstaff, AZ, USA

E. Lellouch Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique (LESIA), Observatoire de Paris, Meudon, France

Rosaly M. C. Lopes Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

Kathleen E. Mandt Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA

I. Matsuyama University of Arizona, Tucson, AZ, USA

Alfred S. McEwen Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA

William B. McKinnon Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, Saint Louis, MO, USA

L. C. Quick NASA Goddard Space Flight Center and The Nexus for Exoplanet System Science (NExSS), Greenbelt, MD, USA

Jani Radebaugh Brigham Young University, Provo, UT, USA

J. A. Rathbun Planetary Science Institute, Tucson, AZ, USA

Paul M. Schenk Lunar and Planetary Institute, Houston, TX, USA

Nicholas M. Schneider Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO, USA

John R. Spencer Department of Space Studies, Southwest Research Institute, Boulder, CO, USA

Terry-Ann Suer Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA, USA

A. Trinh University of Arizona, Tucson, AZ, USA

David A. Williams Arizona State University, Tempe, AZ, USA

Chapter 1
Introduction

Rosaly M. C. Lopes, Katherine de Kleer, and James Tuttle Keane

Abstract The Galilean satellite Io is a dynamic body in the solar system and a prime location to study volcanism. We summarize the content of the chapters in this book and provide a table of basic orbital and physical properties.

Io was discovered by Galileo Galilei on 8 January 1610 and has fascinated scientists ever since. The innermost of Jupiter's four Galilean satellites (Fig. 1.1, Table 1.1), Io is the only body in our solar system besides Earth known to have large-scale active volcanism (Fig. 1.2). Io has an important role in our understanding of the Solar System, as it is one world where we can observe extreme processes *in action*, including tidally-powered volcanism, tectonism, and atmospheric and magnetospheric interactions. Io's heat flow is much higher than the Earth's, its interior may contain a magma ocean (Fig. 1.3), and its lavas may be hotter than any erupted on the Earth today. Io's intense volcanism makes it the best present-day analogue for the early Earth and other rocky worlds, and likely for some present-day exoplanets and exomoons.

Since the discovery of active volcanism on Io from *Voyager 1* images in 1979, our knowledge of Io has evolved considerably (Fig. 1.4). While the *Voyager 1* and *Voyager 2* flybys gave us a glimpse of a world that few had imagined, the *Galileo* mission in the 1990s and early 2000s provided a much deeper knowledge of Io and the Jupiter system. Despite complications with the mission, *Galileo* revolutionized our understanding of the Jupiter system, including revealing the tantalizing possibility that tidal dissipation not only fuels the volcanoes on Io, but also supports subsurface water oceans beneath the icy shells of Europa and Ganymede. The amazing findings of *Galileo* at Io inspired a previous book, *Io After*

R. M. Lopes (✉) · J. T. Keane
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA
e-mail: Rosaly.m.lopes@jpl.nasa.gov; James.t.keane@jpl.nasa.gov

K. de Kleer
California Institute of Technology, Pasadena, CA, USA
e-mail: dekleer@caltech.edu

R. M. C. Lopes et al. (eds.), *Io: A New View of Jupiter's Moon*, Astrophysics and Space Science Library 468, https://doi.org/10.1007/978-3-031-25670-7_1

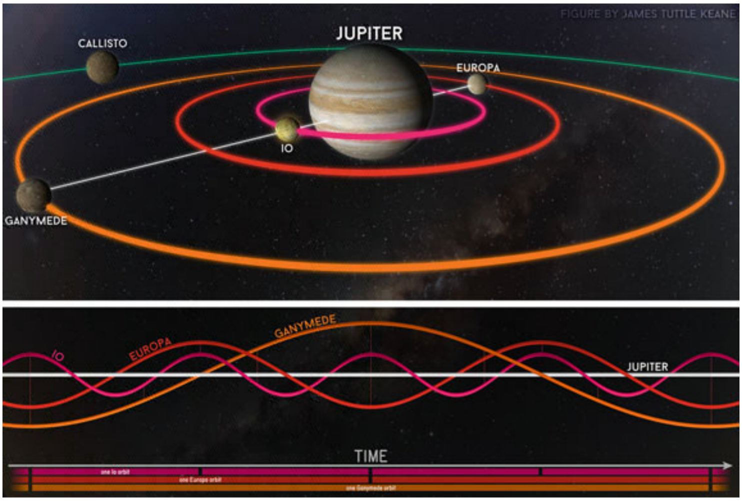

Fig. 1.1 A schematic of the Jupiter system. The top panel shows a perspective view of the Jupiter system. The relative sizes of the orbits are to scale, as are the relative sizes of the moons, although the orbits and moons are not to scale with each other, nor is Jupiter to scale with anything. The bottom panel shows a simplified view of the configuration of the three satellites in the Laplace resonance (Io, Europa, and Ganymede) as a function of time. Thin, vertical dashed lines indicate different conjunctions and oppositions of the satellites. Figure credit: James Tuttle Keane, NASA's Eyes on the Solar System (https://eyes.nasa.gov/)

Table 1.1 Io's basic orbital and physical properties

Mean radius:	1821.6 ± 0.5 km
Bulk density:	3528 ± 3 kgm^{-3}
Orbital period:	1.769 days (42.459 h)
Orbital eccentricity:	0.0041 (forced)
Orbital inclination	0.037°
Orbital semimajor axis:	421,800 km
Rotational period:	Synchronous (identical to orbital period)
Mass:	$(8.9320 \pm 0.0013) \times 10^{22}$ kg
Surface gravity:	1.796 ms^{-2} (18.3% Earth gravity)
Global average heat flow:	>2.5 Wm^{-2}
Core dynamo magnetic field strength:	<50 nT
Geometric albedo:	0.62
Local topographic relief:	<17 km
Number of active volcanic centers	>166
Typical surface temperatures:	85 K (night)140 K (day)1000~2000 K (erupted lavas)
Atmospheric pressure:	<10^{-9} bar

Source: Lopes, R. and D. Williams: Io after Galileo. *Reports on Progress in Physics*, Institute of Physics Publishing, 68, 303–340

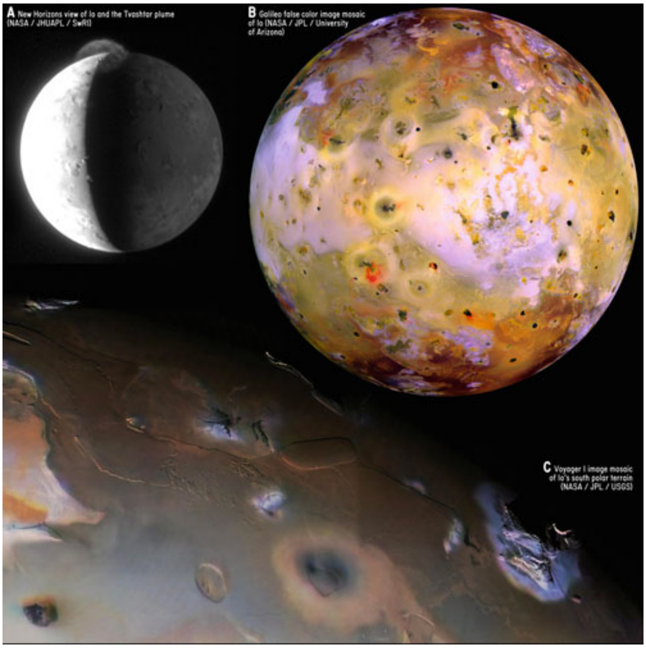

Fig. 1.2 Images of Io and its dramatic activity. (**a**) A New Horizons view of Io and, with the Tvashtar plume prominently extending above the limb. The left-hand side of Io is illuminated by sunlight, while the right-hand-side of Io is partially illuminated by Jupiter-shine. (**b**) A Galileo false color image mosaic of Io. (**c**) A Voyager 1 image mosaic of Io's south polar terrain. The terminator (line between daylight and night) runs diagonally across the frame. On the right is Haemus Mons, a 10-km tall mountain. Volcanic plains, plateus, and crater-like depressions (patera) cover the rest of the scene. Figure credit: James Tuttle Keane, NASA, JHUAPL, SwRI, JPL, University of Arizona, USGS

Galileo (Editors: R.M.C. Lopes and J.R. Spencer), published in 2007. That same year saw new observations of Io and the Jupiter system from the *New Horizons* spacecraft on its way to Pluto. The *Juno* spacecraft has been in orbit of Jupiter since 2016, and while the primary goal of the *Juno* mission is to understand Jupiter, *Juno* has provided exciting serendipitous views of Io. *Juno* is expected to have several close flybys of Io late in its extended mission. Simultaneously, ground- and space-based astronomy has advanced rapidly: adaptive optics observations have provided sharper views of Io, and synoptic monitoring is revealing intriguing patterns in the cadence of Io's volcanic activity. New observatories have enabled detailed views of Io at wholly new wavelengths, including the Atacama Large Millimeter Array (ALMA). The combination of observations have allowed great strides to be made on understanding Io, and more recent models have gained us knowledge of Io's formation and interior.

This past decade of advances motivated the need for an updated review book of Io, to build on and complement *Io After Galileo*. The scope, and chapters, are

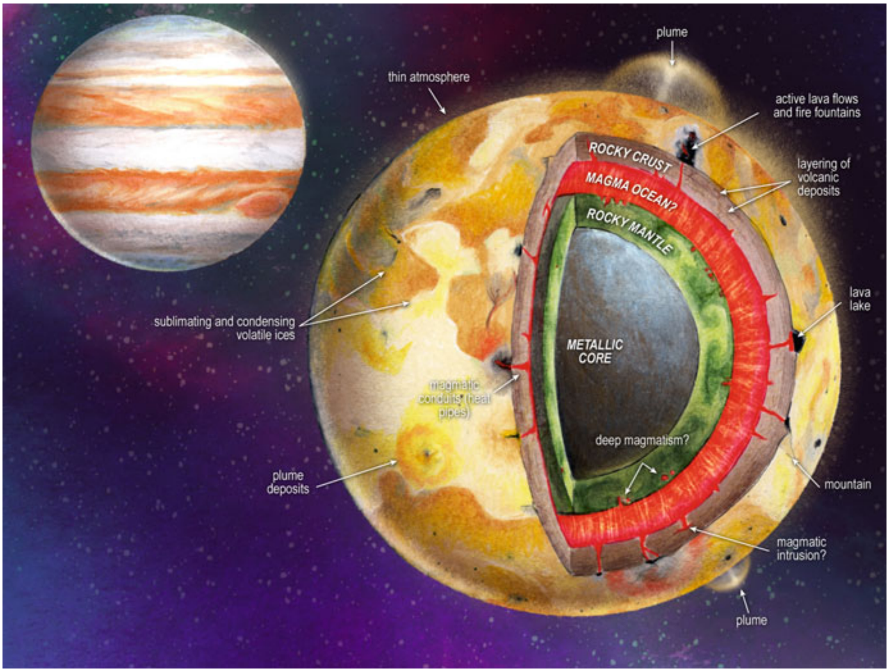

Fig. 1.3 Schematic illustration of the possible interior structure of Io, and the various processes shaping Io. Figure credit: James Tuttle Keane and Aaron Rodriquez

different from those of the 2007 book, as we have chosen to highlight the areas where significant progress has been made since then:

In *Chap.* 2, Nick Schneider and John Spencer take a thematic approach to the extraordinary discoveries made about Io, from early telescopic observations to present-day telescopic and space-based observations. It complements the comprehensive review of pre-*Galileo* results in *Io After Galileo*.

In *Chap.* 3, William McKinnon discusses the formation and earliest evolution of Io, reviewing the new models that have caused significant changes in our prior understanding. Since Galileo data were acquired in the 1990s and early 2000s, astronomical observations of protoplanetary disks, including those by ALMA, plus advances in theoretical and numerical models have enabled significant progress in our understanding satellite formation and evolution scenarios.

In *Chap.* 4, James Tuttle Keane, Isamu Matsuyama, Carver J. Bierson, and Antony Trinh review the major advances in our understanding of Io's interior structure and the fundamental process of tidal heating evolution since the *Galileo* era. Advances in geophysics provide the context for interpreting Earth-based observations, which are often designed to interrogate Io's interior structure and evolution, and have seen tremendous advances in the last couple of decades.

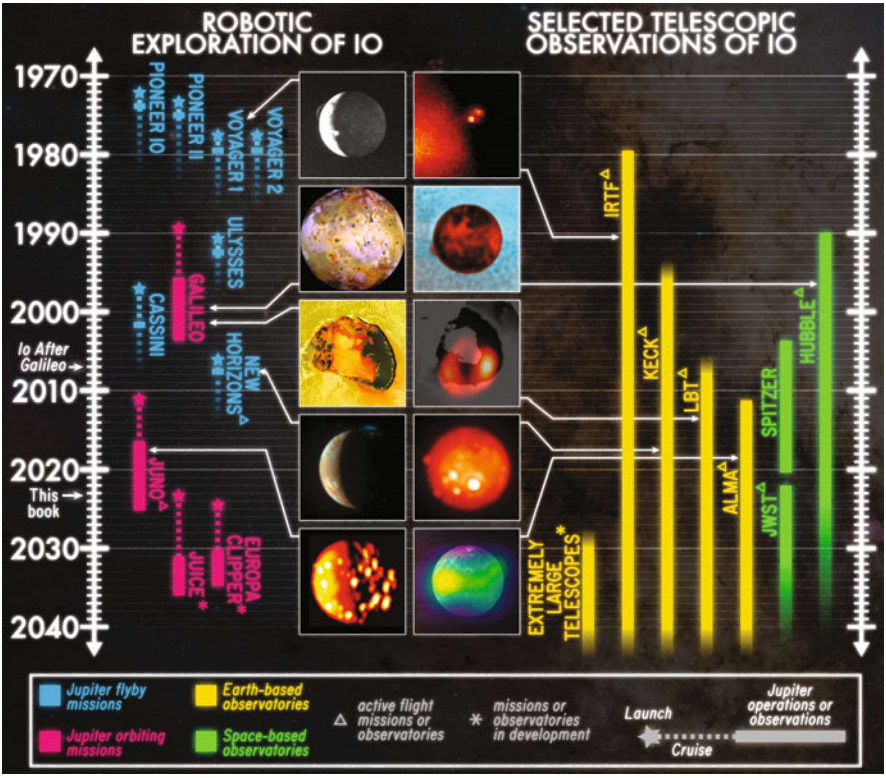

Fig. 1.4 Timeline of robotic and telescopic observation of Io. The left-hand side shows robotic exploration of Io, and all spacecraft that have flown through the Jupiter system and observed Io. The right-hand side shows a subset of ground- and space-based telescopic observations of Io. There is an extensive history of ground-based observations prior to the 2000s, which is more thoroughly detailed in *Io After Galileo*. All future dates should be taken as notional. "Extremely Large Telescopes" include the European Extremely Large Telescope (EELT), Giant Magellan Telescope (GMT), and Thirty Meter Telescope (TMT). Figure credit: James Tuttle Keane, and references therein

In *Chap.* 5, David Williams, Paul Schenk, and Jani Radebaugh review Io's surface geology, which is unique in the solar system as it is completely dominated by volcanic and tectonic features. Io's extreme volcanism causes a resurfacing rate that has effectively erased all impact craters from the surface, making Io the only object in the Solar System on which no impact craters have been identified.

In *Chap.* 6, Katherine de Kleer and Julie Rathbun discuss Io's thermal emission and heat flow. Io's surface shows many sources of thermal emission (hot spots) and, although many of these were detected from *Galileo* data, our understanding of the hot spots and heat flow, both volcanic and passive, has progressed substantially since the end of the *Galileo* mission due to new telescopic datasets, continuing analyses of spacecraft data, and improvements in theoretical models.

In *Chap.* 7, Laszlo P. Keszthelyi and Terry-Ann Suer review the many different, but indirect, constraints on the bulk composition Io. The chapter focuses on bulk composition rather than surface composition, since there have been few new observations of Io's surface composition since Galileo. In this chapter, the authors use a detailed consideration of Io's lavas to illustrate how decades of research have bounded, but not pinned down, the chemistry of Io.

In *Chap.* 8, Imke de Pater, David Goldstein, and Emmanuel Lellouch review our latest knowledge of the plumes and atmosphere of Io with an emphasis on research conducted since the *Galileo* era. While the primary source of Io's atmosphere is sublimation of SO_2 frost, volcanoes can have a substantial effect on the atmosphere as shown both via observations and model simulations. Although considerable progress has been made towards both a characterization and understanding of Io's atmosphere, there are some fundamental questions that are still unanswered.

In *Chap.* 9, Fran Bagenal and Vincent Dols review the major role that Io plays in Jupiter's giant magnetosphere and how, in turn, magnetospheric particles and fields affect Io. They discuss the physical processes that shape the space environment around Io and the impact from Jupiter out into interplanetary space. Since *Galileo* observations, data from *New Horizons*, *Hubble Space Telescope*, the Japanese *Hisaki* satellite, and the *Juno* spacecraft have made significant contributions to our understanding of the space environment of Io.

In *Chap.* 10, Amy Barr, Ramon Brasser, Vera Dobos, and Lynnae C. Quick discuss how Io can be an analogue for tidally heated exoplanets. The conditions we see at Io—a rocky body orbiting close to its parent planet, in resonant orbit with its sibling satellites and experiencing intense tidal heating, also occur in at least one system of a star and its planets, TRAPPIST-1. The chapter discusses the use of simple geophysical models, which reproduce observed behaviors of Io, to show that the TRAPPIST-1 bodies may be in a similar geophysical regime as Io.

In *Chap.* 11, Alfred McEwen, Amanda F. Haapala Chalk, Laszlo P. Keszthelyi, and Kathleen E. Mandt review the key outstanding questions and future observations of Io, including future telescopic and spacecraft observations. The chapter reviews what instruments and observations might be made by a future mission and why Io is so important as a target for future exploration.

NASA's long-term goals are defined by Decadal Surveys conducted by the National Academies of Science, Engineering, and Medicine. The most recent Decadal Survey, *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032* prioritized Io science. Origins, Worlds, and Life identified 12 priority science questions, and Io features prominently in the majority—with particular strong connections to priority science questions related to the evolution of solid body interiors, circumplanetary systems, and dynamic habitability.

At the time of writing, we look forward to future spacecraft observations of Io by NASA's *Juno* spacecraft, currently in orbit around Jupiter, and the European Space Agency's *JUpiter ICy moons Explorer* (*JUICE*) spacecraft, scheduled to arrive at the Jupiter system in 2031. Dedicated Io missions have been, and we expect will continue to be, proposed under NASA's competitive programs, including NASA's New Frontiers 5 opportunity and Discovery.

It is our hope that this book will serve as inspiration for researchers and students to familiarize themselves with the state of our understanding of the most extreme and unique worlds in our Solar System.

Acknowledgements J.T.K. carried out a portion of this research at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004). R.M.C.L.'s work was done as a private venture and not in the author's capacity as an employee of the Jet Propulsion Laboratory, California Institute of Technology.

Chapter 2
Understanding Io: Four Centuries of Study and Surprise

Nicholas M. Schneider and John R. Spencer

Abstract We now know Io to be a world of superlatives among solar system bodies. It experiences the strongest orbital resonances, exhibits the greatest volcanic activity, sustains the most rapidly escaping atmosphere, and lies deep within the most powerful magnetosphere. This chapter synopsizes the centuries of studies that revealed Io's remarkable properties, but highlights how the fundamental interconnectedness between these distinct properties were revealed only in recent decades. In fact, the revelation of links between seemingly unrelated planetary phenomena placed Io in the position to revolutionize planetary science. Before Io, who might have hypothesized that orbital peculiarities could drive volcanoes, shrink moons and power aurora? Io's example forces planets and moons to be studied as coupled as systems, from celestial mechanics through interiors, surfaces, and atmospheres to magnetospheres.

2.1 Introduction

The history of Io studies shows that many of its exceptional properties were quick to reveal themselves through observation, but the connections between them took time to appreciate. In the pages that follow, we'll see repeated cases where the "superlatives" of Io's properties lead to the earliest discoveries of new planetary processes, starting with its very discovery along with the other Galilean moons

---

The original version of this chapter has been revised. A correction to this chapter can be found at https://doi.org/10.1007/978-3-031-25670-7_12

N. M. Schneider (✉)
Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO, USA
e-mail: Nick.Schneider@lasp.colorado.edu

J. R. Spencer
Department of Space Studies, Southwest Research Institute, Boulder, CO, USA
e-mail: spencer@boulder.swri.edu

R. M. C. Lopes et al. (eds.), *Io: A New View of Jupiter's Moon*, Astrophysics and Space Science Library 468, https://doi.org/10.1007/978-3-031-25670-7_2

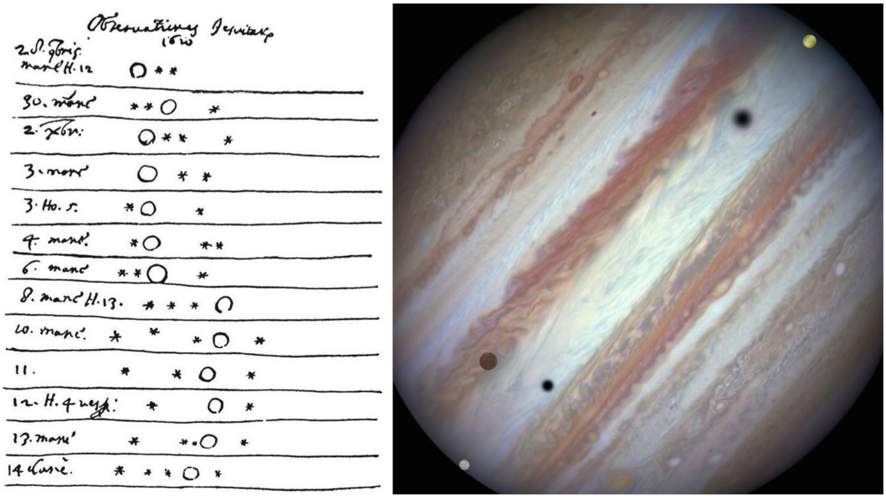

Fig. 2.1 Galileo's discovery drawings of Jupiter's moons from 1610 (left) contrasted with a Hubble Space Telescope image for (right) showing three moons against Jupiter

(Fig. 2.1a). The trend continues to this day, establishing Io as the prototype for tidal heating, atmospheric escape and many other processes. In this role it has inspired explorations of countless other objects where similar processes may play out in less dramatic fashion. Beyond our solar system, Io informs studies of planets around other stars, where Io's superlatives must certainly be outdone within the astonishing diversity of exoplanets.

The interconnectedness of Io phenomena present a challenge to any attempt to summarize the history of its exploration. A strictly chronological exposition can be as confusing to the reader as it was to those who were making the discoveries. And a topical structure inevitably loses focus on the links between the topics. We therefore have taken an approach highlighting our understanding of the connections themselves, which often spanned a decade or more to come in focus.

In the sections that follow we'll review the early days of discovery, and then explore six fundamental breakthroughs in Io science and planetary science:

- Celestial mechanics drives tidal heating
- Tidal heating controls internal structure and heat flow
- Heat flow generates diverse volcanic styles
- Volcanism creates a unique surface
- Volcanism supplies an atmosphere out of balance
- Rampant atmospheric escape fuels the magnetosphere

Each section follows the initial decades or centuries of study from groundbased observations, and is then abruptly punctuated by the flood of results from the Voyager spacecraft. Figures have been selected to pair the initial discoveries with the current state-of-the-art, demonstrating how far we have come. For instance, each of the six stories below is transformed by the Io plume discovery photo

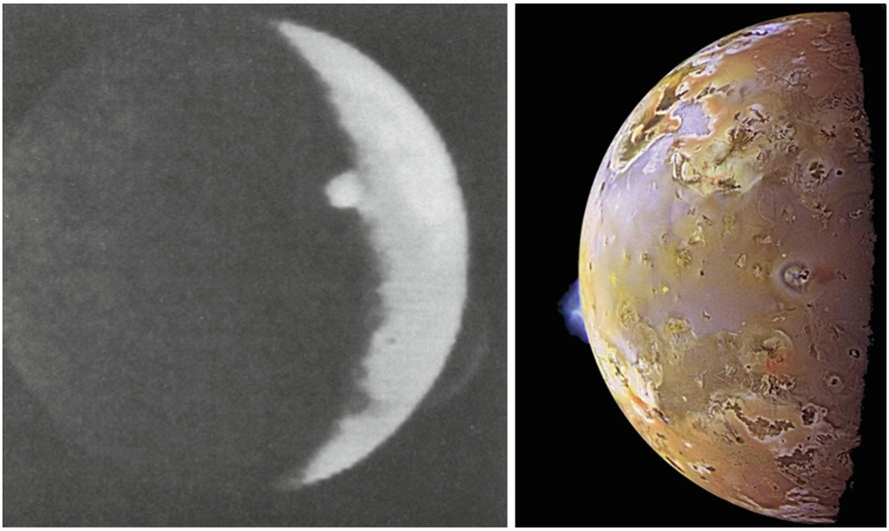

Fig. 2.2 Voyager's plume discovery image from 1979 (left; Morabito et al. 1979), compared to a Galileo plume image from 1997 (right; NASA PIA01081)

(Fig. 2.2a, described in more detail in Sect. 2.5), arguably among the most revolutionary images in all of planetary science. The accompanying results from other instruments were as profound, if less visually staggering. The ensuing years of spacecraft visits, extraordinary observations from Earth, critical theoretical and modeling efforts, bring us to our current understanding.

This chapter benefits tremendously from prior histories of Io exploration which take more traditional chronological and topical approaches, specifically chapters in *Satellites of Jupiter* (Morrison 1982) *Satellites* (Burns and Matthews 1986), *Jupiter: The Planet, Satellites and Magnetosphere* (Bagenal et al. 2004), and reviews by Spencer and Schneider (1996), Cruikshank and Nelson (2007) and de Pater et al. (2021). In addition, each chapter within this volume lays out the critical history of their subjects.

Countless Io presentations over the decades have included the cartoon of six blind men examining different parts of an elephant, each with a contradictory interpretation and none getting a sense of the whole being. The analogy would be better if the six blind people were examining an alien, something we still don't know quite what it looks like.

2.2 Discovery and Bulk Properties

It is not surprising that Galileo Galilei and Simon Marius, the first two people to point telescopes to the heavens, should quickly discover moons around Jupiter. Their size and proximity render them technically bright enough to be naked-eye objects, though Jupiter's glare prevents clear detections. They travel farther in the sky from Jupiter than moons of other planets, and their rapid orbital motion quickly differentiates them from the fixed stars.

Galileo in Italy and Marius in Germany were contemporaries and competitors in this endeavor, and in the late days of 1609 were both observing the moons of Jupiter and documenting their positions. It was Galileo who published first, honoring his sponsor by naming them the Medicean Moons. Marius published later, offering the individual names (as suggested to him by Kepler) that we still use today. The confusing fact that Galileo's observing logs were dated in the "new" Gregorian calendar while Marius' were recorded in the old Julian calendar is a commentary on the religious and societal schisms of the time. It is perhaps fitting that the moons today are collectively named after Galileo while they carry the individual names proposed by Marius.

The importance of Jupiter's moons in subverting geocentrism cannot be overstated, but it is not central to the discoveries to come. What is relevant is the recognition that these newly discovered objects were potentially useful in both practical and exploratory ways. Galileo noticed that the repeatability of the moons' appearances and disappearances against Jupiter's disk offered the possibility of measuring "absolute time", by which observers anywhere on earth could witness the events and agree on the time. This could potentially solve the longstanding "longitude" problem in navigation at sea. Solar time, relative to the ship's location, could readily be observed; the addition of an absolute time reference would permit calculation of longitude. The concept was sound when applied through measurements on land, but in the end it proved impractical to make the necessary astronomical observations of these occasional phenomena from shipboard.

Increasingly complete and accurate tabulations of orbital phenomena established a long baseline which proves valuable even today. The orbit sizes and periods validated Kepler's Third Law when it was published a decade after the moons' discovery. In 1675, Roemer also noticed that the time between repeating phenomena was stable when Jupiter was closest or farthest, but lost or gained time in between. He recognized that could only happen if light took a finite time to cross the diameter of Earth's orbit, about 16 min. Modern-day readers will recognize this as twice the 8 min for the Sun's light to reach Earth, though an actual measurement of the speed of light in physical units needed to wait a century for a measurement of the Astronomical Unit. Roemer he never published his results, but his time estimate leads to an error of less than 2% in the speed of light.

The determination of the Astronomical Unit in the 1700s would have permitted an early insight into Jupiter's nature, thanks again to Io's orbital motion. The absolute size of Jupiter would have been known to be about ten times Earth from its telescopic angular diameter and distance from Earth. Similarly, Io's orbit would be recognized as nearly the same as that of Earth's moon. If Jupiter and Earth were composed of the same materials, Newton's law of gravitation would predict Io's orbital period to be about 22 h. Its actual value of 42 h is incontrovertible evidence of Jupiter's low density compared to Earth, even without knowing the value of the gravitational constant. It's not clear who, if anyone made this leap in understanding.

By the late 1800s, telescopes were capable of resolving Io's 1.2 arc-second disk frequently enough to investigate the nature of the body itself. The appearance was initially puzzling: against empty space, Io appeared elongated parallel to Jupiter's belts, while against Jupiter's disk, Io appeared as two distinct dark spots displaced perpendicularly to the belts. Barnard (1891a) originally favored the idea that Io was a double object, but eventually concluded (Barnard 1891b, 1894) that both phenomena could be explained if Io's equator were bright and its poles darker. Against the sky, the bright equatorial band would dominate the image, while against Jupiter's bright disk the band would blend in, leaving the dark poles as distinct objects. Barnard (1897) soon measured Io's angular diameter which translated to 3950 km, less than 10% above the modern value. Better accuracy only came much later, when Io occulted the star Beta Scorpii, and yielded a diameter of 3656 ± 5 km (Taylor 1972).

With Io's physical size first constrained by Barnard (albeit a slight overestimate), Laplace's dynamically-deduced mass (see Sect. 2.3) was used to derive Io's density. Initial calculations (Russell et al. 1945) found values around 2.7–2.9 g/cm^3, lower than the modern value of 3.5 g/cm^3 but high enough to correctly conjecture that Io must be made mostly of rock and metal. The same method gave lower densities for Ganymede and Callisto, hinting at the trend which drives theories on the formation of these moons. The Pioneer spacecraft flyby's gave definitive measurements of Io's density at 3.53 g/cm^3 and the declining trend with distance from Jupiter (Andersson et al. 1974).

Small, repeatable brightness variations with orbital phase demonstrated that Io and the other Galilean moons orbited synchronously (Stebbins 1927). As higher precision became possible, Binder and Cruikshank (1964) reported the phenomenon of post-eclipse brightening, in which Io's brightness exceeded its pre-eclipse value by 10% for about 10–20 min before lowering again. They proposed that an atmosphere was partially condensing on the surface as it cooled in Jupiter's shadow. Many subsequent efforts could not reproduce effects of this amplitude, though Nelson et al. (1993) did find occasional brightenings of a few percent in some cases. Disk-resolved imaging from Voyager, Galileo and Hubble (Veverka et al. 1981; Burrati et al. 1995; Secosky and Potter 1994, respectively) showed negligible effects at a global level though regional variations could not be ruled out. Fanale et al. (1981) and Nelson et al. (1993) concluded that the timescales for condensation was marginally plausible, but that the quantity necessary to brighten the surface globally (several mm thick) was not available in the atmosphere nor could it all sublime quickly enough. Nonetheless, the supposition that some atmosphere must condense during eclipse continued to drive observational searches and remains a candidate mechanism for many variable phenomena at Io.

By-eye assessments of Io's color and early photometric measurements confirmed Io's reddish color, especially remarkable in contrast to its nearest neighbors. Ever-improving photoelectric measurements allowed multi-bandpass filter measurements (Harris 1961; Johnson and McCord 1971; Morrison et al. 1974), which quantified the red slope of the spectrum and suggested a broad, shallow absorption centered around 600 nm. Io's overall high albedo suggested water ice or frost on the surface.

But the extension of observations to the near-infrared (Kuiper 1957; Moroz 1966; Johnson and McCord 1971) showed Io's reflected solar spectrum to be brighter at 1.6 and 2.2 μm than other moons. This led these observers to conclude that water ice was not a major constituent of Io's surface, contrary to general expectations for moons of the outer solar system.

Io's low reflectance from the blue into the ultraviolet suggested a different constituent: sulfur. Elemental sulfur (S_8) was a good match to the spectrum below 500 nm (Wamsteker 1972; Kuiper 1973). Additional ultraviolet absorptions confirmed by spacebased- (Caldwell 1975) and groundbased-observations (Nelson and Hapke 1978) supported the case for sulfur, including the possibility of other allotropes affected by outgassing or irradiation (Nelson and Hapke 1978).

The identification of sodium and potassium escaping Io (see Sect. 2.5), and Io's overall high red reflectivity led to salt (NaCl) as a potentially major constituent (Fanale et al. 1974). With sulfur and oxygen soon discovered beyond Io, sulfate salts became plausible (Nash and Fanale 1977), and other evaporite deposits not exhibiting water absorptions. Cruikshank et al. (1978) and Pollack et al. (1978) detected a distinct absorption feature at 4.07 μm but were unable to identify candidates for matching surface materials. There was relatively little speculation at the time on how surface processes might have concentrated these constituents in surface layers.

Even from a distance, Voyager imagery quickly confirmed the blurry groundbased view: a bright equator, darkened poles, and an abundance of yellow, orange and red. Laboratory work soon showed that the 4.07 μ absorption feature unidentified in groundbased spectra was wholly consistent with SO_2 frost (Fanale et al. 1979). Soderblom et al. (1980) concluded from Voyager imagery than the principal surface constituents were sulfur dioxide frost and allotropes of sulfur. The explanations for this unique state of affairs are described in Sects. 2.5 and 2.6, and corroborating evidence from atmospheric measurements are covered in Sect. 2.7.

2.3 Celestial Mechanics Drives Tidal Heating

The orbit tabulations by Roemer and later observers caused consternation for Giovanni Cassini and others working towards predictive tables in the late 1600s. Even when corrected for changing Earth-Jupiter distances, the orbits were not sufficiently fixed to be predictable by Kepler's laws (due to effects we now attribute to precession and libration). Tabulations by Pehr Wargentin in 1743 showed conclusively that Io, Europa and Ganymede were locked into a 4:2:1 orbital resonance to astonishingly high accuracy. In 1788, Pierre-Simon Laplace published a mathematical explanation for this fundamental relationship, and was even able to derive approximate masses for the moons based on their mutual gravitational perturbations. Laplace's theory required the moons' orbits to maintain "forced eccentricities" which were so well explained that astronomers became more interested in the minor "free eccentricity" deviations away from those values.

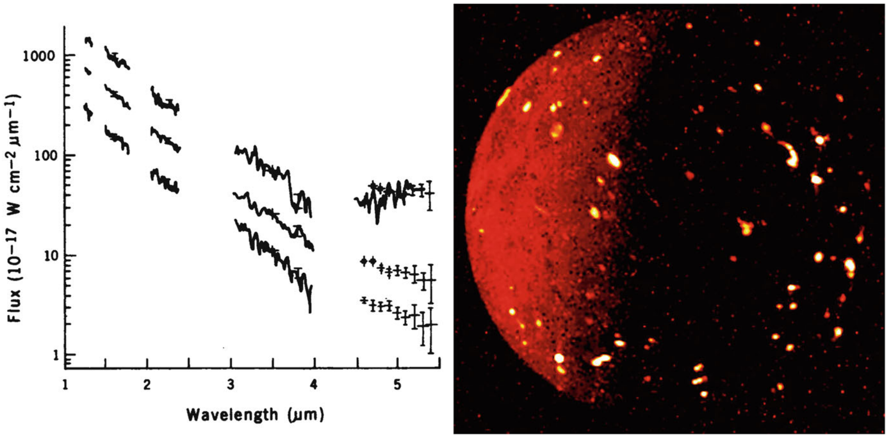

Fig. 2.3 The first strong indication of Io's excess thermal emission from Witteborn's 5 μm brightening (1979, left), compared to hotspots observed by Juno in 2019 (right, NASA PIA25698). In the plot at left, spectra taken over two nights are offset vertically to show the difference at long wavelengths. In the image at right, hotspots appear as points, some with diffraction spikes, with thermal emission from the dayside at left

The orbital resonances were little more than a curiosity for near two centuries. In the late 1970s, the attention of astronomers and planetary scientists was turning to the Jupiter system in anticipation of the arrival of the Voyager 1 spacecraft in March 1979. In February of that year, Witteborn et al. (1979) published observations of an unexpected brightening of 5 μm emission over a period of hours (Fig. 2.3a). They considered thermal emission as an explanation, with 0.01% of Io's surface at 600 K, but rejected it based on experience with objects in the inner solar system. They favored an explanation involving Jupiter's magnetosphere, known by this time to be unusual as we will discuss in Sect. 2.8.

On March 2, 1979, mere days before the Voyager 1 encounter with the Jupiter system, Peale et al. (1979) published their work showing that tidal heating might melt Io's interior and cause active volcanism. Their paper prophetically concludes that "Voyager images of Io may reveal a structure and history different from any previously observed." Their fundamental realization was that tidal heating is driven by the large forced eccentricity, not the nearly-negligible free eccentricity.

Voyager and Galileo stereo imaging bore out the tidal distortion: the bulges were measured at 13 km (Gaskell et al. 1988; Thomas et al. 1998), the largest tidal deformation of any solar system object of that size. Models indicated that Io's orbital motion closer and farther from Jupiter would lead to tens of meters daily variation, greater even that the fluid tides of Earth's oceans.

Io also raises tides on Jupiter, and dissipation inside Jupiter drives orbital evolution of the three resonant moons. Conservation of energy and angular momentum link orbital evolution with tidal heating. Thanks to nearly four centuries of orbital observations, the orbital evolution can be measured and thereby permit an estimate of dissipation in Io and the resulting total heat flux (Ojakangas and Stevenson 1986; Hussman and Spohn 2004; Lainey et al. 2009). Fuller et al. (2016) found that the phenomenon of resonance locking between moons and internal planetary oscillations had the potential to resolve inconsistencies between predicted and measured heat flow, and allows for the possibility of time-variable heat flow on geological timescales. The deposition of tidal heat controls Io's interior structure. Models by Seagatz et al. (1988) revealed that the tidal heating is not uniform in Io's interior, which can significantly affect heat flow to the surface. In fact, it's possible that tidal heating creates a magma ocean, an idea supported by an induced magnetic field potentially observed by Galileo (Khurana et al. 2011).

For greater detail on Io's interior and tidal heating, see Chap. 4 by Keane et al.

2.4 Tidal Heating Controls the Interior and Heat Flow

Following the Peale et al. (1979) theoretical proof of tidal heating, the full picture rapidly emerged: orbital resonances cause tidal heating in the three innermost Galilean moons, with Io most affected. Witteborn's infrared excess was a large volcanic eruption caused by this heating. Prior observations of unexpectedly high heat flux in eclipse could be properly attributed to volcanic activity and not unusual thermal inertia properties (Hansen 1973; Morrison and Cruikshank 1973). The "heat pipe" model (O'Reilly and Davis 1981) provided a key insight into Io's heat transport, in which heat is primarily advected at hotspots and not conducted through the lithosphere. This allows for a thicker and more rigid lithosphere capable of supporting the rugged topography observed in some locations. Lithospheric thickness may also be controlled by magmatic intrusions (Spencer et al. 2020).

Voyager's IRIS instrument confirmed the hotspot concept (Hanel et al. 1979), though initial estimates of the hotspot temperature were complicated by the instrument's limited wavelength coverage and the large fraction of field of view containing cooler surrounding areas. Modeling of a two-temperature surface suggested hotspot temperatures of 290 K. Hanel et al. recognized that using three temperature regions might allow a better fit with higher temperatures, potentially as high as sulfur's melting temperature of 385 K.

Thus began decades of productive and insightful infrared observations from Earth and interplanetary spacecraft. The Galileo mission orbited Jupiter from 1995 to 2003, carrying a powerful near infrared mapping spectrometer (NIMS). NIMS could spatially resolve hotspots during Io encounters and measure their thermal emission with enough spectral coverage to identify multiple components. The SSI CCD imager identified volcanic centers system and provided visible wavelength context. The Cassini mission performed a gravity assist at Jupiter and obtained low spatial resolution visible images of Io; like the Galileo SSI, its longest visible wavelength bandpass was sensitive to the hottest lava flows. New Horizons also took advantage of a Jupiter gravity assist, and obtained visible and IR imaging of Io. The

Juno spacecraft now orbits Jupiter, and its infrared instrument has obtained stunning images of Io hotspot thermal emission (e.g., Fig. 2.3b).

The long gaps between spacecraft observations were used to great advantage with groundbased telescopes. Initially, low spatial resolution prevented identification of more than a few of the very brightest features, but ingenious observing plans extracted a wealth of information. Jupiter's disk could be used as an occulting edge while Io passed behind, and the infrared brightness could be measured at sufficient time resolution to tie the drops in emission with their location in one dimension across the disk (Spencer et al. 1991). The geometry was limited to the Jupiter-facing hemisphere, but opportunities presented themselves many times per week, and hundreds of observations have been taken over the years (Fig. 2.4a). Similarly, Io's occasional occultation by other jovian moons allowed the occulting disk to cover and uncover Io's hotspots (e.g., Goguen et al. 1988). This gave more precise location information, thanks to the sharper edge of the satellite disk and the combined ingress and egress. But opportunities were rare and came in seasons separated by 6 years.

Adaptive optics changed the game for Io hotspot studies, allowing a dozen or more hotspots to be mapped and measured in a single observation. Since the geometry didn't require a particular orbital geometry, all of Io could be mapped and much greater temporal coverage obtained (Fig. 2.4b).

The Earth-based and space-based observations strove to address the same key issues: What is Io's total heat flow, and how much can be attributed directly to the volcanic hotspots? Where are Io's volcanic hotspots located, and how do they vary? Can their spectra constrain temperature and magma composition?

The first question has the most straightforward answers: Io emits about 100 TW of power (Johnson et al. 1984; Veeder et al. 1994; Rathbun et al. 2004; McEwen et al. 2004), with just over half coming from the 242 identified volcanic hotspots (Veeder 2015, and prior work described therein). A single volcanic center, Loki, may be responsible for 20% of the hotspot emission. Curiously, the other ~50%

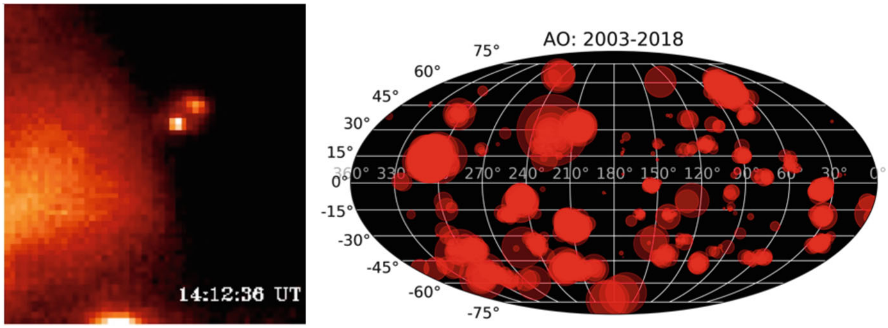

Fig. 2.4 A 3.8 μm NASA/IRTF image from Spencer et al. (1991) of Io with two visible hotspots passing behind Jupiter's limb (left), compared to de Kleer et al.'s (2019a) cumulative hotspot map (right). Power is indicated by spot size

of the total heat flow cannot be traced to regions on the surface or other heat transport processes according to the analysis of Veeder et al. (2012). The average heat flux on Io is ~2.5 W/m^2, compared to Earth's value of ~0.1 W/m^2. Earth's total power output is only ~50 TW, less than Io's despite 12 times great surface area. Heat sources other than tidal heating are negligible, contributing only about 1% in comparison (McEwen et al. 2004).

The holy grail for volcanologists was an accurate measurement of the highest temperature possible of the erupting lava. This would constrain what material was being erupted: elemental sulfur, as originally proposed, could not exceed 600 K, a silicate of basaltic composition was limited to 1475 K, and ultramafic silicates could reach 1800 K. The nature of the lava composition plays into every aspect of Io's solid body: the internal composition and temperatures, the "plumbing" and pressure that supplies magma to the surface, the viscosity and material properties of erupting lava, and the strength and rheological properties of lava long after it has solidified. Central to interpreting measurements were models of the thermal emission predicted from erupting and cooling lava flows (Davies 1996; Howell 1997; Keszthelyi and McEwen 1997).

Even on the Earth it's not easy to measure the hottest temperature a lava can reach, so remote sensing methods face an even greater challenge. On Earth, a volcanologist would have to make a measurement of hot lava and none of the adjacent materials: the narrow orange-hot crack in a lava flow or lava lake, without the adjacent solidified material still at very high temperature. Remote sensing methods at best combine hot and warm materials in the field of view; since lava can cool 400 K in 2 min on Io, it's likely that the warm areas dominate the signal. Furthermore, the hottest lava's emissions extend into the visible wavelength range and can be challenging to quantify in the presence of sunlight. In principle, multiple components and backgrounds can be modeled and fit to the observations, but the uncertainty of the highest temperatures can be too large to draw a definitive conclusion on the magma composition. There's little substitute for a direct measurement of the hottest component.

The quest for Io's hottest temperatures began with the Pearl et al. (1979) measurement of $T = 290$ K for a single component or possibly 385 K for multiple components at Loki. Both values were seen as consistent with molten sulfur but did not constitute evidence for silicate lava. However, Pearl and Sinton (1982) found much higher temperatures, up to 650 K, in IRIS spectra of the volcano Pele. Johnson et al. (1988) inferred temperatures of at least 900 K, requiring silicates, in ground-based observations of a large eruption in 1986, and Stansberry et al. (1997), using shorter-wavelength ground-based data, found temperatures of at least 1400 K. McEwen et al. (1998) examined Galileo SSI observations of an apparent fire-fountain eruption at the Pillan hotspot, finding a temperature of >1600 K, requiring ultramafic composition. Davies et al. (2001), incorporating NIMS data and cooling models increased the estimated eruption temperature to >1870 K. Keszthelyi et al. (2007) reanalyzed the observations and found a peak observed temperature closer to 1340 K, more consistent with basaltic composition, though eruption temperatures could be higher.

The hotspot locations from Earth and space together give a sense of fairly uniform coverage in longitude, and a slight preference for equatorial and mid-latitudes (perhaps due to observational bias). There are slightly more volcanoes on the Jupiter-facing hemisphere, and a handful of volcanoes at high latitudes. These may be clues to where and how tidal heating is generated and transported in the interior, but the evidence does not yet favor or rule out any such models.

The Loki hotspot, which is likely a lava lake 200 km in diameter, is large enough that spatial temperature variations across its surface can be mapped and observed to vary with time. Occultation measurements allowed determination of where within the lava lake the highest temperatures were observed. As on terrestrial lava lakes, the cool crust is likely denser than the underlying molten lava, so the lake is unstable against foundering. The changing location of the highest temperatures has been interpreted as a wave of foundering circulating around the perimeter of the lake, taking more than a year to do so (Rathbun et al. 2004; Davies 2003).

Succinctly summarizing the temporal behavior is considerably harder. Hotspots and plumes were originally categorized as persistent or transient (Lopes-Gautier et al. 2000), only to later find that some volcanic centers changed categories in both directions on timescale of a decade. Some hotspots have been observed more than a hundred times, and others only once.

Loki again offers the best temporal study as its substantial brightness allows frequent measurements. Periodicity studies initially identified a period of 540 days (Rathbun et al. 2002), but a longer baseline and new analysis shows that a shorter period of 460–480 days is also consistent with the observed variability (de Kleer and de Pater 2017; de Pater et al. 2017; de Kleer et al. 2019a). These values coincide with periodic changes in Io's eccentricity and semimajor axis, suggesting that celestial mechanics affects tidal flexing in a manner that affects an active volcanic eruption (de Kleer et al. 2019a). More observations will be required to verify this result.

Juno's JIRAM instrument is capturing the most recent close-up imaging of Io's hotspots. Mura et al. (2020) have taken advantage of Juno's polar orbit to identify the first of south polar hotspots on Io, and five more in previously unimaged areas. Juno's extended mission offers even more opportunities, and the last views until the arrival of Europa Clipper anticipated in 2030.

For a closer look at Io's individual hotspots and their diverse behaviors, see Chap. 6 by de Kleer & Rathbun.

2.5 Heat Flow Generates Diverse Volcanic Styles

The story behind Fig. 2.2a's plume discovery image from Morabito et al. (1979) reveals the stochastic process of science as well as anything else in this chapter, and should be required knowledge for anyone studying Io. While the predictions of volcanism by Peale et al. (1979) had appeared days before the Jupiter encounter, no observation changes were possible. So while the surface did look truly bizarre, and