Io After *Galileo*

A New View of Jupiter's Volcanic Moon

Rosaly M. C. Lopes and John R. Spencer

Io After *Galileo*

A New View of Jupiter's Volcanic Moon

Springer

Published in association with
Praxis Publishing
Chichester, UK

PRAXIS

Dr Rosaly M. C. Lopes
Jet Propulsion Laboratory/NASA
Pasadena
California
USA

Dr John R. Spencer
Department of Space Studies
Southwest Research Institute
Boulder
Colorado
USA

SPRINGER–PRAXIS BOOKS IN ASTRONOMY AND PLANETARY SCIENCES
SUBJECT *ADVISORY EDITORS*: Philippe Blondel, C.Geol., F.G.S., Ph.D., M.Sc., Senior Scientist, Department of Physics, University of Bath, UK; John Mason, B.Sc., M.Sc., Ph.D.

ISBN 3-540-34681-3 Springer Berlin Heidelberg New York

Springer is part of Springer-Science + Business Media (springer.com)

Bibliographic information published by Die Deutsche Bibliothek

Die Deutsche Bibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available from the Internet at http://dnb.ddb.de

Library of Congress Control Number: 2006928061

Printed in Germany

Cover design: Jim Wilkie
Project management: Originator Publishing Services, Gt Yarmouth, Norfolk, UK

Printed on acid-free paper

Contents

To our late colleagues Damon Simmonelli and Bill Sinton,
who greatly contributed to our understanding of Io.
We miss their scientific insight, humor, and friendship.

Preface

This book is a community effort that grew largely out of the informal Io workshops that have happened since the early 1990s. In the first few years, the purpose of the workshops was to determine which *Galileo* observations would be key to further our understanding of this exotic moon. Since *Galileo*'s main antenna did not open, the number of observations taken by the spacecraft was exceedingly small compared with other missions; it was therefore imperative to decide which observations would be the highest priority. We can make an analogy between a tourist with a point and shoot camera, taking pictures at a high rate to decide later which are the best, and Ansel Adams, spending many hours or even days deciding how best to take a single shot.

The competition for resources on *Galileo* was fierce, but those of us in charge of Io observations for *Galileo*'s instruments decided at an early stage that much could be gained from collaboration. Thus, the workshops evolved into the planning of collaborative observations and dividing resources between us in a mostly peaceful manner. By the time we began acquiring *Galileo* Io data, in 1995 for fields and particles and 1996 for remote sensing, a *Galileo* Io working group was already well established, paving the way for collaborative research. As the years passed, the workshops became more aligned with data analysis and, finally, we started discussing key questions such as how hot Io's magma really is, and what key future observations we will need to answer the many unsolved mysteries that Io continuously threw our way. When the *Galileo* mission ended in 2003, we felt the time was right for a book reviewing the state of knowledge after *Galileo*. Hopefully, it will serve as a guide for future work, be it in the form of new space missions, telescopic observations, data analysis, or modeling.

We would like to thank all the people who participated in these workshops over the years and, in particular, all those who took on the task of organizing them. We thank Clive Horwood from Praxis for inviting us to take on this book project,

Neil Shuttlewood and his team for editing and pre-press book production, and Jim Wilkie for the cover design.

Many of the authors in this book reviewed one anothers chapters, but we are also deeply appreciative of the help from other reviewers: Robin Canup, Lazlo Kezthelyi, Susan Kieffer, Margaret Kivelson, Jack Lissauer, Ellis Miner, Jeff Moore, Neil Murphy, Jani Radebaugh, Julie Rathbun, Bill Smythe, Tilman Spohn, David Stevenson, Nick Thomas, and Bill Ward. Others who provided invaluable assistance include Daniel Beuchert, Mark Boryta, Lou Glaze, Benedicte Larignon, Michelle McMillan, Dennis L. Matson, Chris Moore, Stan Peale, Carl B. Pilcher, William Sheehan, Laurence Trafton, Philip Varghese, Glenn J. Veeder, Andrew Walker, and Ju Zhang. Many of the authors are supported by NASA research grants and we acknowledge the support from NASA's Planetary Geology and Geophysics Program, the Jovian System Data Analysis Program, and the Outer Planets Research Program. We also wish to thank the Center for Adaptive Optics and Science and Technology Center (STC), the National Science Foundation, and the Hubble Space Telescope Archive Program. Most importantly, we thank the *Galileo* Flight Team, whose enormous dedication and ingenuity enabled us to have a successful mission despite numerous problems. We also thank our fellow science team members, principal investigators, project managers, and the *Galileo* Project Scientist, Torrence Johnson. *Galileo* increased our knowledge of the Jupiter system by orders of magnitude and we are deeply grateful to all who contributed.

Rosaly M. C. Lopes,
Jet Propulsion Laboratory, Pasadena, California
John R. Spencer,
Southwest Research Institute, Boulder, Colorado

Figures

Tables

Abbreviations and acronyms

ADONIS	Adaptive Optics Near-Infrared System
AKR	Auroral Kilometric Radiation
AMU	Atomic Mass Unit
AO	Adaptive Optics
AU	Astronomical Unit
CAI	Calcium–Aluminium Inclusion
CFB	Continental Flood Basalt
CFD	Computational Fluid Dynamics
COS	Cosmic Originas Spectrograph
DDS	Dust Detector Subsystem
DSMC	Direct Simulation Monte Carlo
EPD	Energetic Particles Detector
ESO	European Southern Observatory
EUV	Extreme UltraViolet
FOS	Faint Object Spectrograph
FWHM	Full Width at Half-Maximum
GEM	*Galileo* Europa mission
GHRS	Goddard High-Resolution Spectrograph
GMM	*Galileo* Millennium Mission
GSMT	Giant Segmented Mirror Telescope
HIC	Heavy Ion Counter
HST	Hubble Space Telescope
IRIS	InfraRed Imaging Spectrograph
IRTF	InfraRed Telescope Facility
ISO	International Space Observatory
ISS	Imaging Science Subsystem
IUE	International Ultraviolet Explorer
JOI	Jupiter Orbit Insertion

JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
KH	Kelvin–Helmholtz
LBT	Large Binocular Telescope
LGA	Low-Gain Antenna
LTE	Local Thermodynamic Equilibrium
MAG	MAGnetometer
MMSN	Minimum-Mass Sub-Nebula
MMT	Multi-Mirror Telescope
NIMS	Near-Infrared Mapping Spectrometer
OSIRIS	OH-Suppressing InfraRed Imaging Spectrograph
OWL	OverWhelmingly Large Telescope
PLS	PLasma detector Subsystem
PPR	PhotoPolarimeter and Radiometer
PMS	Pre-Main-Sequence
PWS	Plasma Wave Subsystem
SB	Stochastic–Ballistic
SPIFFI	SPectrograph for Infrared Faint Field Imaging
SSI	Ssolid-State Imaging system
STIS	Space Telescope Imaging Spectrograph
SZA	Solar Zenith Angle
TEXES	Texas Echelon Cross Echelle Spectrograph
TMT	Thirty Meter Telescope
UVS	UltraViolet Spectrometer
VIMS	Visible–Infrared Mapping Spectrometer
VLT	Very Large Telescope

Contributors

Chapter 1
Alfred S. McEwen
University of Arizona

Chapter 2
Dale P. Cruikshank
NASA Ames Research Center

Robert M. Nelson
Jet Propulsion Laboratory

Chapter 3
Jason E. Perry
University of Arizona

Rosaly M. C. Lopes
Jet Propulsion Laboratory

John R. Spencer
Southwest Research Institute, Boulder

Claudia J. Alexander
Jet Propulsion Laboratory

Chapter 4
William B. McKinnon
Washington University in St. Louis

Chapter 5

William B. Moore
University of California, Los Angeles

Gerald Schubert
University of California, Los Angeles

John D. Anderson
Jet Propulsion Laboratory

John R. Spencer
Southwest Research Institute, Boulder

Chapter 6

Elizabeth P. Turtle
Johns Hopkins University Applied Physics Laboratory

Windy L. Jaeger
U.S. Geological Survey, Flagstaff

Paul M. Schenk
Lunar and Planetary Institute

Chapter 7

David A. Williams
Arizona State University

Robert R. Howell
University of Wyoming

Chapter 8

Paul E. Geissler
U.S. Geological Survey, Flagstaff

David B. Goldstein
University of Texas, Austin

Chapter 9

Robert W. Carlson
Jet Propulsion Laboratory

Jeffrey S. Kargel
University of Arizona

Sylvain Douté
Laboratoire de Planétologie de Grenoble

Laurence A. Soderblom
U.S. Geological Survey, Flagstaff

J. Brad Dalton
NASA Ames Research Center

Chapter 10

Emmanuel Lellouch
Observatoire de Meudon

Melissa A. McGrath
NASA Marshall Space Flight Center

Kandis Lea Jessup
Southwest Research Institute, Boulder

Chapter 11

Nicholas M. Schneider
University of Colorado

Fran Bagenal
University of Colorado

Chapter 12

Franck Marchis
University of California, Berkeley

John R. Spencer
Southwest Research Institute, Boulder

Rosaly M. C. Lopes
Jet Propulsion Laboratory

1

Introduction

Alfred S. McEwen

Io is the innermost of the four large Galilean satellites of Jupiter, discovered by Galileo Galilei in 1610. This discovery proved that planetary bodies can orbit something other than Earth and confirmed the Copernican view that the Sun is the center of the Solar System. In 1771 Pierre-Simon Laplace described what is now called the Laplace resonance, in which every time Ganymede orbits Jupiter once, Europa orbits twice, and Io four times. Thus, these large satellites periodically line up with Jupiter. It would take more than 200 years for scientists to appreciate the significance of this observation to Io and Europa.

Prior to *Voyager* spacecraft exploration, there were many clues to the fact that Io was unusual. Fanale *et al.* (1978) wrote: "Observations of line emission from neutral and ionic species in the Io-surrounding cloud, reflectance studies and theoretical considerations suggest Io's surface is unlike that of any other body in the Solar System." They proposed that radiogenic and accretional heat could have transported salt-rich solutions to the surface, leaving behind a layer of evaporite deposits. Recent results have shown this prediction to be remarkably prescient, that is, for Mars (Squyres *et al.* 2004).

Peale *et al.* (1979) realized that the Laplace resonance created a significant forced eccentricity in the orbits of Io and Europa, so these bodies would be deformed periodically while orbiting massive Jupiter, leading to significant internal heating or tidal energy. They predicted that Io would have sufficient heat generation to lead to runaway melting of the interior, and that the *Voyager* spacecraft would observe manifestations of this heat flow. Indeed, shortly after publication of Peale *et al.* (1979), the *Voyager 1* encounter revealed the bizarre volcanic terrains, active plumes, and thermal anomalies ("hot spots"). *Voyager* also revealed mountains more than 10 km high, inconsistent with runaway melting under a thin crust – because the heat is lost primarily via volcanic eruptions rather than conduction through a thin lithosphere.

Io's mean radius and bulk density are similar to the Moon, but whereas the last volcanic eruption on the Moon was more than 1 or 2 billion years ago, Io has hundreds of active volcanic centers. Terrestrial volcanologists say an active volcano is one that has erupted in historic times; each and every volcano that is identifiable on Io's surface may have been active in the past few centuries. Thus, Ionians reserve "active" for a volcano that is erupting lava or pyroclastics and gas in such great quantities that it can be detected in very remote observations, including from Earth. When it comes to our Solar System, Io is by far the most volcanically active, although Mustafer (the lava planet in Star Wars Episode III) seems comparable.

This book contains review chapters by the leading experts in the study of Io. Cruikshank and Nelson begin with a history of Io exploration, from ground-based telescopic studies through the era of spacecraft exploration (*Pioneer*, *Voyager*, and *Galileo*). Much of the rest of the book focuses on the most recent results, primarily from *Galileo*'s tour of the Jovian system from 1995–2003 (Chapter 3) and modeling motivated in part by these results. McKinnon *et al.* discuss the formation of Io in the proto-Jovian nebula and its orbital and thermal evolution. The life history of the terrestrial planets is like that of a mortal person (birth, young and active, declining activity, death), whereas some outer planet satellites have histories more like Buddhist reincarnation, with large fluctuations in tidal heating and internal activity.

Subsequent chapters review current knowledge about Io from the inside out, like an atom of sodium that first resides in Io's interior, rises toward the surface in a convection cell, erupts in an active volcano, then gets sputtered from either the hot lava surface or from a tall plume into the atmosphere and into Jupiter's powerful magnetosphere. Moore *et al.* review the internal structure and tidal heating of Io, which is unique among the silicate planets due to its current heat flow, but may provide insight into processes that operated very early in the histories of the terrestrial planets. Io's geologic activity is the result of how Io transfers heat from the tidally flexed interior to the surface and to space. Moving upward to the crust, Turtle *et al.* review the tectonics of Io, producing impressive but still puzzling features like the mountains and paterae (calderas or volcanic–tectonic depressions).

The most spectacular phenomena on Io are the active volcanic eruptions. Williams and Howell review current knowledge about effusive eruptions of lava on Io, including the discovery of very high-temperature lavas, which may be analogous to ancient terrestrial ultramafic lavas. Io's lavas seemed to get hotter over time from the *Voyager* era through the *Galileo* era, similar to the shrinkage over time in estimates of Pluto's diameter, but both trends are actually due to increasingly accurate measurements. Geissler and Goldstein next review the spectacular volcanic plumes, up to 500 km high, and their surface deposits; they reach the important conclusion that McEwen and Soderblom (1983; my first paper) were not entirely wrong. Carlson *et al.* review the current knowledge about the composition of Io's surface, based in large part on results from the near-infrared mapping spectrometer (NIMS) on *Galileo*.

Moving outward, Lellouch *et al.* review the current thinking about Io's tenuous but dynamic atmosphere, dominated by SO_2 from a combination of volcanic outgassing and sublimation of surface frosts. Next Schneider and Bagenal review the complex interactions between Io and the Jovian magnetosphere.

The final chapter by Marchis *et al.* reviews outstanding questions (there are many) and prospects for future exploration of Io. The Earth-based telescopes keep achieving better observations, and *New Horizons* will provide a glimpse of Io on its way to Pluto/Charon. However, we really need a dedicated Io mission, one that can monitor Io at high spatial and spectral resolution, in order to make major advances. Everyone seems to love Io, but a dedicated mission has not yet been given a high priority in any of the studies or planning documents of NASA or the National Academy of Sciences. Mars, Europa, and Titan are higher priorities in the quest to understand the origin(s) of life, and Io is also a difficult world to explore, deep in Jupiter's harsh radiation environment. But eventually Io's day will come, and it is sure to be a dazzling show.

REFERENCES

Fanale, F. P., Johnson, T. V., and Matson, D. L. 1977. Io's surface and the histories of the Galilean satellites. In: J. Burns (ed.), *Planetary Satellites*. University of Arizona Press, Tucson, pp. 379–405.

McEwen, A. S. and Soderblom, L. A. 1983. Two classes of volcanic plumes on Io. *Icarus*, **58**, 197–226.

Peale, S. J., Cassen, P., and Reynolds, R. T. 1979. Melting of Io by tidal dissipation. *Science*, **203**, 892–894.

Squyres, S. W., Grotzinger, J. P., Arvidson, R. E., Bell, J. F., Calvin, W., Christensen, P. R., Clark, B. C., Crisp, J. A., Farrand, W. H., Herkenhoff, K. E. *et al.* 2004. In-situ evidence for an ancient aqueous environment on Mars. *Science*, **306**, 1707–1714.

2

A history of the exploration of Io

Dale P. Cruikshank and Robert M. Nelson

> *"On the 7th day of January in the present year, 1610, in the first hour of the following night, when I was viewing the constellations of the heavens through a telescope, the planet Jupiter presented itself to my view, and as I had prepared for myself a very excellent instrument, I noticed a circumstance which I had never been able to notice before, namely that three little stars, small but very bright, were near the planet; and although I believed them to belong to the number of the fixed stars, yet they made me somewhat wonder, because they seemed to be arranged exactly in a straight line, parallel to the ecliptic, and to be brighter than the rest of the stars, equal to them in magnitude ... When on January 8th, led by some fatality, I turned again to look at the same part of the heavens, I found a very different state of things, for there were three little stars all west of Jupiter, and nearer together than on the previous night ..."*
>
> Galileo Galilei, *Siderius Nuncius*, March 1610
> Translation by E. S. Carlos (Shapley and Howarth, 1929)

2.1 THE DISCOVERY AND EARLY OBSERVATIONS OF THE GALILEAN SATELLITES

2.1.1 From Medician Star to a world of its own

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

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

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

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

---

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

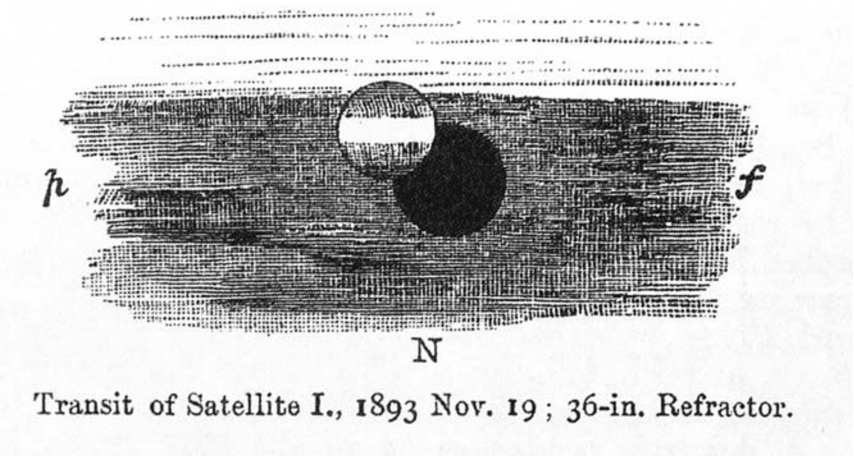

Figure 2.1. Appearance of Io against the disk of Jupiter during the transit of 19 November 1893. Observed by E. E. Barnard with the Lick Observatory 36-inch refractor, and clearly showing the dark polar regions and bright equatorial band of Io (Barnard, 1894).

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

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

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

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

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

2.2 WHAT IS THE NATURE OF IO?

2.2.1 A paradigm emerges

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

---

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

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

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

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

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

---

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

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

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

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

2.2.2 New technology enables new observations

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

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

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

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

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

---

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

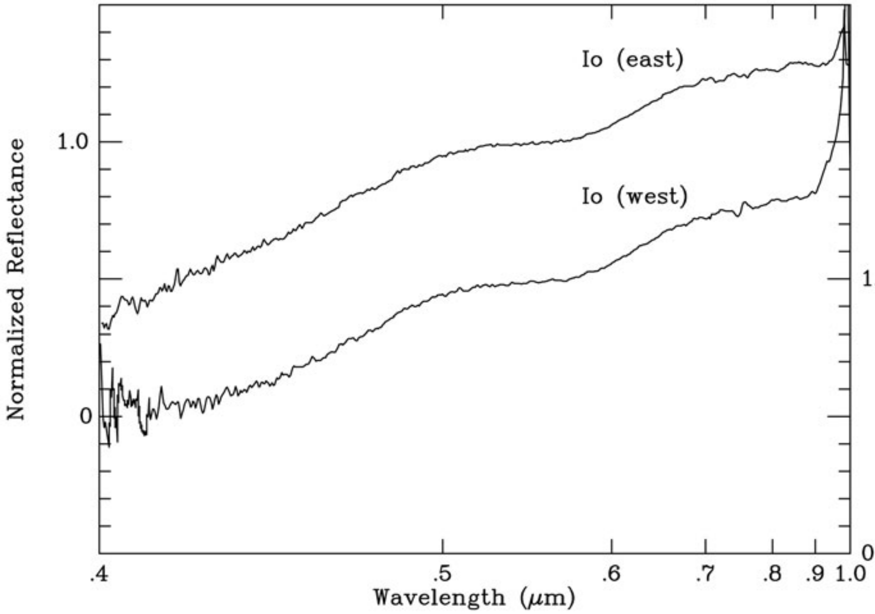

Figure 2.2. Normalized spectra of Io at western and eastern elongations in 1973, ratioed to a solar-type star (Wisniewski and Andersson, 1973, unpublished). These spectra confirm the broad absorption, 500–600 nm, first noted by Johnson and McCord (1971). The scale on the left abscissa refers to Io (east),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

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

---

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