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Outstanding questions and future explorations

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12.1 INTRODUCTION

Although our knowledge of Io had been significantly advanced by several missions (*Pioneer 10* in December 1973, *Pioneer 11* one year later, and especially the *Voyager* twin probes in 1979), the arrival of the *Galileo* spacecraft in 1995 brought unprecedented opportunities to observe Io. *Galileo* orbited the Jovian system for 8 years, obtaining numerous observations of Io in several wavelength ranges (Chapter 3). The study of these data, complemented by recent data from ground-based telescopes and the Hubble Space Telescope (HST), has revolutionized our understanding of the nature of this most exotic moon. The previous chapters have summarized the state of our knowledge of Io, from the interior to the torus, and made clear that many key questions remain unanswered. After the demise of *Galileo*, these questions must be addressed by continuing work on already acquired data, by new ground-based and space telescope observations and, in the future, by new missions to the Jupiter system with dedicated observations of Io. Table 12.1 reviews the capabilities of several facilities (spacecrafts and telescopes) which were used or are in development to study this captivating satellite of Jupiter.

Io is a key target for future exploration. It is a fascinating world in its own right and, as the most dynamic body in the Solar System, this satellite occupies a unique place in planetary science. It is the only place beyond Earth where we can watch active volcanism happen on a large scale. The interconnections between orbit dynamics, interior, tectonics, volcanism, surface chemistry, and atmosphere, and the associated magnetospheric phenomena, can significantly help our understanding of the evolution of planets and satellites. Io is the best target for the study of tidal heating, a process of fundamental importance to the evolution of planetary satellite systems, and one that may greatly expand the habitability zone for extra-terrestrial life. Io's tidal heating is intimately connected to Europa's, which is thought to maintain an ocean of liquid water underneath an icy crust (e.g., Greeley *et al.*, 2004).

Table 12.1. Overview of facilities (spacecraft and telescopes) used or proposed to study Io.

Mission or telescope	Year of fly-by operation (performed or scheduled)	Instruments	Spatial resolution on Io	Main scientific results
Pioneer 10	December 1973	Radio, UV, IR photometers + visible imaging	No images recorded due to radiation	
Pioneer 11	December 1974	Radio, UV, IR photometers + visible imaging	1 visible image (resolution of 376 km) seen from North Pole	Characterization of the surface
Voyager 1	March 1979	IR spectrometer, visible camera (IRIS)	1 km in visible	Discovery of volcanic activity, 9 active centers, surface morphology, plumes
Voyager 2	July 1979	IR spectrometer, visible camera (IRIS)	10 km in visible	Study of 8 eruptions, surface morphology, plumes
Galileo spacecraft	December 1995–September 2003	SSI, NIMS, UVS, PPR, fields and particles (Chapter 3)	7 fly-bys, best visible resolution ~6 m, best IR (NIMS) ~1 km	~160 hot spots detected, plumes, close-up of eruptions, fields and particles data
Cassini spacecraft	January 2001	CIRS, ISS, UVIS, VIMS	60 km in visible	Two giant plumes, aurora, Pele activity
Hubble Space Telescope	Since 1990	UV–visible–NIR camera/spectrometers	~200 km in optical	Plume compositions, surface change
ESO-3.6 m + ADONIS	1996–2001	NIR + Thermal IR camera	~250 km in NIR	Hot spot activity
Keck-10 m + AO	Since 2000	NIR + thermal IR camera + spectro	~100 km in NIR	Hot spot activity and temperature, SO distribution
Gemini + GPI	2010	NIR + thermal IR camera + spectro	65 km in R-band (visible)	Hot spot activity and temperature, surface changes
TMT-30 m	April 2014	Undefined but visible + NIR camera + spectro	40 km in NIR 10 km in visible	Hot spot activity and temperature, surface changes
OWL-100 m	Complete in 2020	Undefined but visible + NIR camera + spectro	10 km in NIR	Hot spot activity and temperature, surface changes and morphology
New Horizon fly-by	February–March 2007	UV, visible, NIR camera + spectro	20 km	High-temperature volcanism, plumes, interaction with magnetosphere, SO emission

Io can help us better understand the early Earth, as Io provides a living example of how a planet responds to high heat flow analogous to the Earth's heat flow at the time life began. Io's prodigious volcanic activity, and possible ultramafic composition of the lavas, give us the opportunity to understand the Earth's early geologic activity. Io also provides an ideal testbed for understanding fundamental atmospheric, planetary escape, and magnetospheric processes.

12.2 OUTSTANDING ISSUES

12.2.1 Interior structure and relationship to the heat flow

What is the composition of the core?

A precise tracking of the *Galileo* spacecraft during its five fly-bys of Io satellite has provided new constraints on its interior. It is now clear that Io is a differentiated body consisting of a metallic core and a silicate mantle (Chapter 5). Gravity measurements, which were successfully collected during four fly-bys (Anderson *et al.*, 2001) indicate that Io has a large core (between 0.37 and 0.52 times Io's radius, see Chapter 5), probably made of iron or iron sulfide as predicted by cosmochemical considerations (Consolmagno, 1981). In Chapter 5, the authors discuss the absence of a magnetic field signature, which was not detected even during the late *Galileo* fly-bys a few hundred kilometers above the north and south poles (Kivelson *et al.*, 2001; Kivelson *et al.*, 2004). This implies that little convection is taking place in the core of the satellite. The composition and origin of the core of Io remains uncertain. Better constraints on core composition will be difficult without *in situ* seismic data, but modeling of the chemistry of Io's volcanic gases can perhaps provide some constraints (Zolotov and Fegley, 2000).

What is Io's total heat flow?

An accurate measurement of the heat flow and its variability with time provides important constraints for the interior of Io. Io's rampant volcanism results from the dissipation of energy produced by tidal and orbital interactions with Jupiter, Europa, and to a lesser extent, Ganymede (Peale *et al.*, 1979; Hussmann and Spohn, 2004; see also Chapter 5). Several measurements of Io's heat flow using several techniques and instruments have been published (Matson *et al.*, 1981; Veeder *et al.*, 1994) yielding a minimum average heat flow of 2.5 W m^{-2}. Veeder *et al.* (2004) developed a new model (3 ± 1 W m^{-2}) including the surprisingly warm polar regions observed with *Galileo*/ photopolarimeter and radiometer (PPR) (Spencer *et al.*, 2000), and attributed these to an excess of endogenic heat due to a different style of volcanism at high latitudes (Rathbun *et al.*, 2004). However, uncertainties remain and most heat flow estimates are model dependent. To better understand the mechanism of tidal dissipation, the evolution of Io into the Laplace resonance, and its relation with Europa tidal heating, accurate measurements of Io's heat flow and its temporal variation is needed. Though this task can be addressed through improved models and intensive ground-based observations, these should preferably be combined with spacecraft observations to broaden the wavelength and phase angle coverage.

What is the thickness of the lithosphere?

The thickness of the lithosphere is model dependent and several estimates, ranging from a few km to 100 km, have been proposed (Schubert *et al.*, 2004). However, a lithosphere thickness less than 30 km is inconsistent with the ~10 km heights of mountains on Io (Carr *et al.*, 1998). These mountains are evenly distributed on the surface of Io and most of those imaged by *Galileo* and *Voyager* show tectonic origin (Jaeger *et al.*, 2003). A minimum thickness of 12 km is necessary to form them by compressive stress at the base of the lithosphere, a scenario proposed by Schenk and Bulmer (1998). For a thick lithosphere (>30 km), magma advection is probably the main mechanism for transport of heat across the lithosphere instead of heat conduction. If conduction is negligible, an important consequence is that the remotely measured volcanic heat flows reported previously should therefore correspond to the total heat loss.

The origin of the mountains is still unclear (Chapter 6). Schenk *et al.* (2001) pointed out that if they are considered to be upthrust blocks, the lithosphere should be at least as thick as the tallest mountains (Boösaule Montes has a height of 17.5±3 km). In fact, the lithosphere may not be homogeneous, being thicker, for instance, where the mountains are located. High spatial resolution observations of the morphology of mountains through new spacecraft missions could provide direct information on their formation mechanism and further constraints on the lithospheric thickness.

12.2.2 Nature of the active volcanic centers

How does volcanism operate in extreme environments?

The modeling of eruptions through measurement of their thermal output as a function of wavelength, position, and time (e.g., Davies *et al.*, 2001; Williams *et al.*, 2001; Rathbun *et al.*, 2002) provides constraints on the eruptive centers (such as volumetric eruption rate, composition of the lava, type of volcanism). Similar studies are currently performed to study terrestrial volcanoes from Earth orbit (e.g., Harris *et al.*, 1999). For Earth, the analysis is complicated by the presence of a significant atmosphere and also because of the interaction with volatile elements (i.e., water) present on our planet. For Io the low spatial resolution of most available observations introduces uncertainties in the application of models.

The key to the study of the physical processes controlling volcanism is to separate the influences of magma composition and volatiles, tectono-physical processes (e.g., tidally-induced superheating, mantle plume ascent), and local conditions (e.g., gravity). Because of its low gravity, lack of plate tectonics, high magma temperatures, very low atmospheric pressure, and constant activity, Io provides an end-member example where we can test physical models of silicate volcanism. Observations at greater spatial and temporal resolution would be of great value in testing these models and further constraining eruption parameters.

What is the compositional range of Io's magmas?

Very high magma temperatures measured by *Galileo* at Pillan (Chapter 7) suggest ultramafic compositions, at least for one hot spot. This raises the question of how relatively primitive ultramafic volcanism (typically associated with the ancient Archean (3.8–2.5 Ga) on Earth) could persist on such a dynamically active body as Io where extreme differentiation should be expected (Keszthelyi and McEwen, 1997). Either the current style of volcanic activity is a geologically recent phenomenon (i.e., Io has only recently attained its resonant orbit with resulting tidal heating), or remixing of crustal material back into the mantle has prevented differentiation (see Keszthelyi *et al.* (2004) for one theory). Continued measurements of Io's volcanic thermal emission are needed to determine whether other hot spots exhibit similarly high temperatures that could imply that ultramafic volcanism is widespread. Several similar eruptions characterized by a very high temperature of magma and a brief short life (called Pillanian eruptions, see Chapter 7) have been observed with various techniques, such as Tvashtar with *Galileo* (e.g., Williams *et al.*, 2001; Milazzo *et al.*, 2005), and Surt with adaptive optics (AO) from the ground (Marchis *et al.*, 2002). These eruptions correspond to the outbursts seen by photometric measurements from the ground (Stansberry *et al.*, 1997; Howell *et al.*, 2001). Because they are extremely bright and energetic, with relatively large areas of hot materials exposed, these eruptions give us the best opportunity to extract magma temperatures through spectroscopic measurements, before a significant amount of cooling has taken place. Such measurements are needed to constrain the composition of the magma that will provide a vital window into Io's interior composition and structure, and to provide an estimate of the highest lava temperatures. These measurements will be a high priority for future spacecraft exploration, though this question can also be addressed from the ground given enough telescope time to allow detection of the brightest and hottest eruptions, which are quite rare.

How do Io's very large volcanoes work?

The most widespread volcanic landforms on Io are paterae, in which eruptions are mostly confined within a caldera-like depression (Radebaugh *et al.*, 2001; Lopes *et al.*, 2004). A study by Jaeger *et al.* (2003) showed that 41% of the mountains on Io have one or more paterae adjacent to them, indicating a genetic link between mountains and paterae. Since *Voyager*, over 160 active volcanic centers have been observed (Lopes *et al.*, 2004). Their distribution suggests the absence of large-scale plate tectonics on Io. At least 45 of these hot spots were seen active more than 4 times. Many highly persistent hot spots are found inside paterae, notably Loki and Pele. How do these eruptions behave? Are they lava lakes, perhaps constantly overturning (e.g., Rathbun *et al.*, 2002), or are they temporary lava lakes, formed by a process akin to mid-ocean spreading centers on Earth (Gregg and Lopes, 2004)? How is the magma supplied to replenish these eruptions, which last for years or even decades? The presence of multi-kilometer-high eruption plumes that produce various colored pyroclastic deposits on the surface suggests complex interactions between magma and multiple volatile reservoirs, including sulfur, sulfur dioxide, and possibly halides and others. Are magma–volatile interactions restricted to the shallow crust, or is there deeper assimilation and injection of volatiles by ascending magmas? Close-up spacecraft observations at ultraviolet, visible, and infrared wavelengths, with much better temporal and spatial coverage than *Galileo*, provide the best way to answer these questions, but continued ground-based monitoring of thermal emissions may also provide valuable insights.

Does sulfur volcanism exist on Io?

Sulfur is widespread on Io's surface, and sulfur flows may have been emplaced at various hot spots such as Ra Patera and Emakong (Chapter 7). Sulfur volcanism may play a secondary but important role in Io's resurfacing, but so far we have no proof that sulfur-dominated volcanic flows exist. This question can probably only be answered by high-resolution spacecraft observations capable of measuring the peak temperatures of active flows, or resolving the likely distinctive morphology of sulfur flows, as it is difficult to distinguish sulfur flows from sulfur-coated silicate flows using reflectance spectroscopy.

12.2.3 Io's young surface

Composition of surface

The composition of Io's surface is still not well understood. SO_2 frost is ubiquitous, covering most of the surface, and identifying other compounds has been difficult given the spatial resolution of the available observations (Chapter 9). The relationship between surface colors and composition is not straightforward, although the distribution of color units was well characterized by *Galileo*'s observations (Geissler *et al.*, 1999; see also Chapter 9). Composition of the lavas on Io has only been determined indirectly through temperature and the relative roles of basaltic vs. ultramafic compositions have not been established (Chapter 7). Unfortunately, the near-infrared mapping spectrometer (NIMS) grating stopped moving when the instrument started observing Io at high spatial resolution (Chapter 3), therefore, the opportunity to spectrally characterize different geologic units at high spatial and spectral resolution was lost. New spectroscopic observations from spacecraft are needed to determine the composition of lavas and the detailed distribution of SO_2 and other compounds around Io's hot spots.

Resurfacing rate

Io's prodigious volcanic rate means that, even on timescales of months, surface changes can be identified. The lack of impact craters on the surface has long been attributed to the rapid resurfacing rate, however, the nature of the process is still unknown: does the resurfacing happen mostly because of volcanic products such as lava flows or, as suggested by Geissler *et al.* (2004), are plume deposits largely responsible? The fact that most activity on Io seems to be confined inside paterae, possibly as lava lakes (Lopes *et al.*, 2004), and that relatively few large lava flows are seen on the surface has challenged the early assumption that lavas were responsible for the burial of craters. Temporal observations of Io's activity (plume vs. flows and lava lakes) would better constrain the dominant resurfacing process.

12.2.4 Atmosphere and interaction with Jovian magnetosphere

Plumes: nature and formation

Io's volcanic plumes (Chapter 8) were not well studied by *Galileo*, because the low data rate prevented good spatial and temporal coverage, and only one plume source, Prometheus, was imaged at high enough spatial resolution in daylight to provide detailed insights into the plume generation mechanism. The Prometheus data suggest that the smaller "Prometheus-type" plumes are generated not by direct volcanic venting but by hot lavas volatilizing the SO_2-rich substrate (Kieffer *et al.*, 2000; Milazzo *et al.*, 2001). We do not know if all small plumes are generated this way, and we do not understand how this mechanism generates stable, long-lived, often symmetrical plumes. Additional high-resolution imaging of plume sources from future missions is needed to fully understand them, but in the meantime progress can be made in understanding existing data by the further development of numerical models of plume behavior. More detailed analysis of the composition of Prometheus-type plumes, by spectroscopy from future Earth-orbiting telescopes or missions to the Jupiter system are needed to further constrain the composition of the surface volatiles. The composition of the larger, more variable "Pele-type" plumes, which appear to result from direct volcanic venting, provides information on the chemistry of the magmas with which they have equilibrated in the vent, so these plumes will also be important targets for future compositional studies.

Characterization of the atmosphere

Io's tenuous atmosphere, dominated by sulfur and oxygen compounds, was discovered by *Pioneer 10* spacecraft (Kliore *et al.*, 1974). Since then it has been intensively studied in various wavelength ranges from millimeter to ultraviolet. However, a full atmospheric model, taking into account the full complexity of this atmosphere (including the effect of plasma heating and other factors) is not yet available (Chapter 10) and the atmosphere is still not well understood. We do not yet know whether the atmosphere is primarily supported by sublimation of Sun-warmed surface volatiles, or by volcanic venting, so we do not know whether the atmosphere collapses at night. More data on the variation in atmospheric density with surface location, time of day, and heliocentric distance is needed to answer this basic question. Non-volatile species such as the recently discovered NaCl, which cannot be supported by sublimation, should be tracers of direct volcanic input, allowing us to distinguish volcanic and sublimation sources if we could map atmospheric composition at high spatial resolution. In addition, the atmospheric temperature and its vertical variability is still poorly constrained, complicating reconciliation of the disparate source of data on the atmosphere from ultraviolet, infrared, and millimeter wavelengths.

Plasma transport and formation of the torus

The *Galileo* and *Cassini* fly-bys have provided much new information on the interaction between Io and the Jovian magnetosphere, particularly regarding the flux tube that allows the transfer of charged particles between the two bodies. But we still do not understand how variations in Io's volcanoes control the supply of plasma to the torus, mechanisms of dust formation, or many other details of the flow of matter and energy between Io, Jupiter, and the magnetospheric plasma (see Chapter 11 for more details).

12.3 GROUND-BASED TELESCOPES AND NEAR-EARTH TELESCOPES

Until the arrival of a new mission in the Jovian system with dedicated Io observations, the future exploration of Io and study of its volcanism lies for the next several years largely in the hands of ground-based observers.

12.3.1 The promise of ground-based telescope contributions

With the development of space-borne observatories, the ground-based observations of the Solar System objects have been relegated to a secondary place in the last two decades. Despite the large apertures of the recently developed telescopes, the effect of atmospheric turbulences is still preponderant. The angular resolution on the images is limited to *seeing* (i.e., $\sim 0.7''$ in visible light from a very good site such as on the top of Mauna Kea in Hawaii) quite close to the angular diameter of Io ($\sim 1.2''$) at its opposition. In the near-infrared Io can be routinely resolved by direct imaging with useful spatial resolution approaching $0.3''$ (Spencer *et al.*, 1990). To break this "seeing barrier" and access the diffraction-limited resolutions of current telescopes ($0.040''$ in the near-infrared on a 10-m telescope), several techniques, which take advantage of the development of several technologies, have been developed. The concept of adaptive optics (AO) was proposed by Babcock (1953), but it was necessary to wait until the end of the 1980s before the first prototypes (Starfire and Come-on) were developed independently by several groups based in the U.S.A. and France. The AO systems provide in real time an image with an angular resolution close to the diffraction limit of the telescope. Because of technological limitations, linked to the way the wave front is analyzed, most of the AO systems procure a correction that is partial and slightly variable in time in the near-infrared (1–5 μm). These systems were made available to the astronomical community on 4-m class telescopes less than 10 years ago. Marchis *et al.* (2000, 2001) have used the ADONIS AO system on the 3.6-m ESO (European Southern Observatory) telescope to monitor Io volcanic activity over a period of 4 years at a wavelength of 3.8 μm. The spatial resolution obtained in these observations was $0.15''$, or $\sim$500 km on Io. At these long wavelengths, only the brightest hot spots could be seen against the sunlit disk of Io ($\sim$4 per hemisphere) and the measurement of their individual flux was complicated by the limited angular resolution. With the advent of the 8-m class telescopes, the detectability of hot spots on Io increased drastically. Approximately 5–8 active sources were detected on one

3-μm image using the AO system available on the Keck 10-m telescope which provides an angular resolution of 0.05″ at 2.2 μm (i.e., 130 km on Io at its opposition). Because the hot spots can be also seen at longer wavelengths (5 μm), their temperature (between 500 and 1,000 K) and emission area can be also estimated (Marchis *et al.*, 2005). Additionally to these faint active centers, Marchis *et al.* (2002, 2005) reports the detection of several active centers at a shorter wavelength range (<2.5 μm) which have higher temperatures ($T > 1{,}300$ K) and are more energetic. Because these hot spots are detected in a large wavelength range (down to 1 μm on several occasions), it has been possible to constrain the type of activity using a basaltic lava cooling model (Davies, 1996). Surt-2001, the largest eruption ever witnessed in the Solar System, was luckily detected by Marchis' group at its beginning in February 2001 with the Keck AO system. The intensity profile indicates the presence of a vigorous, high-temperature volcanic eruption ($T > 1{,}400$ K), consistent with either a basaltic or ultramafic eruption. The type of eruption that produces this thermal signature (Pillanian) is thought to have incandescent fire fountains of molten lava which can be several kilometers high, propelled at great speed out of the ground by expanding gases, accompanied by extensive lava flows on the surface. The integrated thermal output of this eruption was close to the total estimated output of Io ($\sim 10^{14}$ W, Veeder *et al.*, 1994).

Several AO systems are or will be soon available on 8-m-class telescopes (MMT, GranteCan, LBT) and the AO techniques have become more reliable and accessible to a wider community. The extended temporal baseline of ground-based observations is highly complementary to the intensive but short-baseline coverage provided by spacecraft. Current AO systems provide data with the same or better spatial resolution as most of the global *Galileo*/NIMS observations taken during the *Galileo* tour (i.e. ~200–300 km) (Lopes-Gautier *et al.*, 1999; Douté *et al.*, 2001). A new generation of integral field spectrographs is now commissioned on several 8-m-class telescopes, such as SPIFFI for the VLT 8-m telescope and OSIRIS for the Keck 10-m telescope. By obtaining 2-D spatial coverage and spectral coverage simultaneously, they will give the opportunity to record in half an hour a spectral cube of Io's surface with a much better spectral resolution (R = 1,000–10,000) than *Galileo*/NIMS (R ~ 300) between 0.9 and 2.5 μm, helping to characterize the composition of the surface and the active volcanic centers. Moreover, after a radiation-induced anomaly stopped the movement of the grating, NIMS spectral sampling decreased to 12 wavelengths in the 1.0–4.7-μm range (Chapter 3). Despite this limited spectral coverage, Douté *et al.* (2004) obtained high spatial resolution maps of SO_2 abundance on Io's surface and proposed different mechanisms of formation for these areas linked with thermodynamic and volcanic processes. The spatial resolution of the data provided by the ground-based spectro-imager instruments will not be as high as the best regional maps from the *Galileo*/NIMS instrument (~150 km per pixel compared with 7–25 km per pixel) but they will help to better characterize changes in the composition of the surface due to volcanism (plume deposits, lava flow fields), as well as characterizing the temperature of the bright hot spots.

The next generation of AO systems is currently under development. These new "extreme AO" systems, built mostly to image planets around nearby stars, will

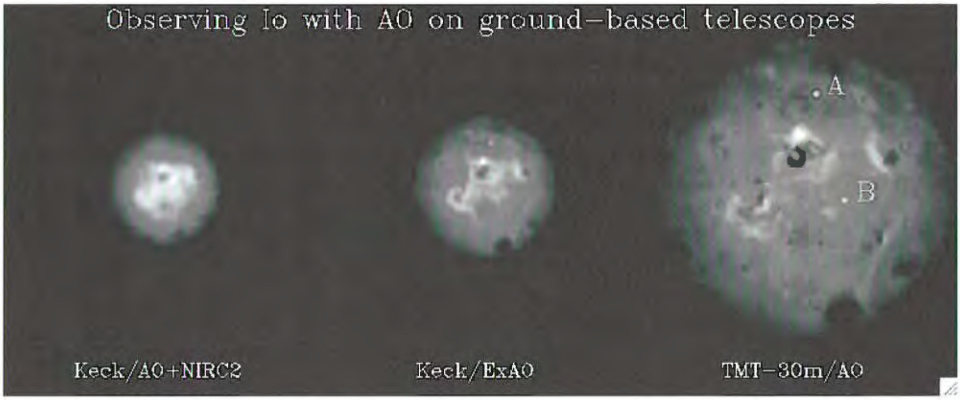

Figure 12.1. Observations of Io in H-band (1.6 μm) with several AO systems. Three AO system performances were simulated. The spatial resolution with the Keck AO is estimated to be 160 km on the center of the disk. An extreme AO system (ExAO) would provide a full correction of the wavefront for such a bright target, providing a sharper image, with a spatial resolution of 120 km on Io. Because of its larger aperture, the spatial resolution of 45 km, attainable on Io with the Thirty Meter Telescope (TMT), would be competitive with most of the global observations recorded by the *Galileo* spacecraft. On rare occasions the thermal output of hot spots is large enough at H-band to be detected in sunlit observations such as these. Thanks to the stability provided by ExAO, hot spot A is detected with this system. Hot spot B, with an intensity 12 times lower than the Keck AO limit of detection is clearly visible in the TMT simulation. More of these high-temperature eruptive centers could be studied with those new instruments helping to better constrain the composition of the magma. No *a posteriori* data processing to enhance the sharpness of the images (such as deconvolution) was applied to these simulations. (See also color section.)

surpass the performance of existing AO systems by two orders of magnitude in contrast – see, for instance, the Gemini Planet Imager instrument for the Gemini telescope (Macintosh *et al.*, 2004). To achieve such nearly perfect and stable correction, the reference targets must be brighter than 8th magnitude in I-band. Extreme AO systems would therefore also have the capabilities to image Io with a quasi-perfect angular resolution (very close to the diffraction limit of the telescope) between 0.6 and 5 μm, corresponding to 45 and 340 km on Io's surface at its opposition. Figure 12.1 illustrates the gain in angular resolution, comparing an extreme AO image taken in H-band (1.6 μm) of Io mounted on the Keck 10-m telescope and the same Jupiter-facing hemisphere observed with the current AO system. In H-band, even after the image was degraded to the resolution provided by the AO system, most of the features detectable are albedo marking such as the dark paterae (Loki patera is discernable at the center of Io) and bright regions covered by SO_2 frost. On rare occasions, when the temperature and surface covered by an active eruption is large enough (typically $T > 1{,}000$ K for $S > 2\,km^2$), its thermal output is sufficiently contrasted to be detected on the sunlit background. On the initial simulated image, we artificially added an eruption north of Loki (in Amaterasu Patera) with intensity four times lower than the limit of detection of Keck AO. Because of the better stability of the extreme AO system, this hot spot is detected on the image provided. Therefore, the study of Io's volcanism (monitoring in particular) will benefit from this planet finder instrument. Infrared or laser-guide-star AO systems have the potential to allow diffraction-limited imaging of volcanic thermal emission in Jupiter eclipse, where high-temperature volcanism can be studied without competition from sunlight. The further promise of obtaining high angular resolution images shortward of 1 μm will be crucial to measuring high magma temperatures, and for imaging Io's plumes. Even at 10 μm, a useful spatial resolution of 600 km is possible on 10-m-class telescopes, allowing the major thermal sources to be detected and their contribution to the total output of Io better estimated.

The instruments mounted on a ground-based telescope are not restrained in size and weight as are those on board space vehicles. They can also be easily updated taking advantage of the most recent technology. For instance, high-resolution spectrographs ($R = 50{,}000$) in the mid-infrared (5–25 μm), such as TEXES (the Texas Echelon Cross Echelle Spectrograph; Lacy *et al.*, 2003), can be used to detect molecules in Io's atmosphere (Spencer *et al.*, 2005), and on large telescopes should allow mapping of the spatial distribution of the atmosphere.

Further advances in ground-based astronomy will come with the likely development in the next two decades of giant segmented mirror telescopes (GSMT). Several competitive projects are under study, such as the Thirty Meter Telescope (TMT) which should be built in partnership between the U.S.A. and Canadian institutes (Figure 12.2), the Euro50 (50 m) telescope, a project established between scientists in Finland, Ireland, Spain, Sweden, and the U.K., and finally the OverWhelmingly Large (OWL 100-m) telescope under study by the European Southern Observatory (ESO). The designs, under study, face several major challenges, such as the design of their enclosure, their weight, and their cost. These future telescopes will be equipped with AO systems (Russell *et al.*, 2004) to allow diffraction-limit performances (i.e., they will provide images with an angular resolution up to the milli-arcsec in the optical). On Figure 12.1, a simulated observation with the TMT 30-m of Io's Jupiter-facing hemisphere in H-band is given for comparison. The gain in angular resolution is sufficient to detect small albedo features at a spatial resolution of 30 km at 1 μm. Another hot spot whose intensity on the initial image was chosen to be 12 times lower than the detection limit of the Keck AO is clearly visible between Loki and Pele (labeled B).

12.3.2 Airborne telescopes

The SOFIA airborne observatory (Erickson, 2005) has the potential to make valuable contributions to the study of Io's atmosphere. Among the instruments being developed for SOFIA is EXES, a high-resolution, mid-infrared spectrograph that will be able to detect atmospheric absorptions from SO_2 and other species at wavelengths, such as the 7-μm region, where observations from the ground are difficult due to atmospheric H_2O absorption.

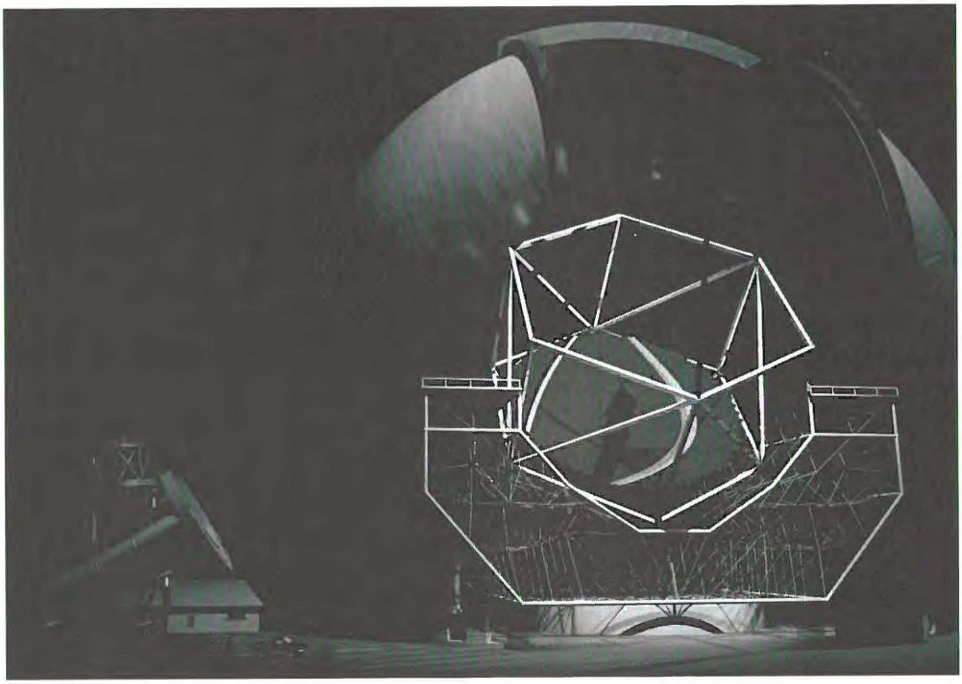

Figure 12.2. Artist's renderings of the TMT and comparison with the Palomar 5-m Hale telescope. This telescope, developed in partnership between the U.S.A. and Canadian institutes should be available in 2014. Because of the large size of its aperture, combined with the capabilities of AO systems, it will provide an unprecedented spatial resolution of Io, better than most of the *Galileo* spacecraft infrared observations (courtesy California Institute of Technology). (See also color section.)

12.3.3 Ultraviolet-dedicated telescopes

The ultraviolet region is largely inaccessible to ground-based observers and has been exploited very recently, mostly with the HST. For instance, the first spectroscopic detection of SO_2 gas (Ballester *et al.*, 1994) in this wavelength range led to numerous works attempting to estimate the distribution of this gas in the thin atmosphere of Io (Jessup *et al.*, 2004 and Chapter 10) and its link with volcanic activity, such as the density of dust particles and gas in the Pele plume. The ultraviolet light is an interesting wavelength range to study the interactions between the surface of Io, its atmosphere, and plasma surrounding the satellite. For instance, far-ultraviolet images of Jupiter from HST reveal polar auroral emissions (Rego *et al.*, 2001), and discrete emission from Io's magnetic footprint (Clarke *et al.*, 2004). Ultraviolet emission of atoms can also be used to detect the neutral cloud made of materials leaving Io (Chapter 11) through several processes. O and S emissions were detected in International Ultraviolet Explorer (IUE) spectra in the corona (at a distance $<500\ R_J$)

and extended clouds, which populates after ionization of the plasma torus. This atmosphere–clouds–plasma–magnetosphere interaction is central to the understanding of the system, but it is as difficult to model as it is to observe (Spencer and Schneider, 1996).

The ultraviolet spectrum shortward of 3,000 Å contains valuable information about Io's atmosphere and its interaction with the Jovian magnetosphere, but can only be observed from space. Io has been explored in this region by a succession of Earth-orbiting spacecraft, particularly the HST, though its ability to study Io in the ultraviolet has been severely hampered by the summer 2004 failure of the Space Telescope imaging spectrograph (STIS), which provided high spatial resolution information (about 20 pixels across Io's disk) on both absorptions by the molecular atmosphere and emission from atomic species. A replacement ultraviolet spectrograph, Cosmic Origins Spectrograph (COS), may be installed on HST if a servicing mission is eventually flown, but its low spatial resolution will limit its capabilities for studying Io. Much more could be done to understand Io's atmosphere and torus interactions with future diffraction-limited ultraviolet telescopes of even modest aperture (1-m aperture could still provide 20 pixels across Io at 2,500 Å), if placed above the Earth's atmosphere and equipped with high-efficiency ultraviolet instrumentation.

12.3.4 James Webb Space Telescope

The James Webb Space Telescope (JWST) is a large infrared-optimized telescope scheduled for launch in August 2013 (Sabelhaus *et al.*, 2005). The telescope will be equipped with a 6.5 m diameter primary mirror providing, therefore, images with an angular resolution no better than the current 10-m class, ground-based telescopes equipped with AO systems. The instrumentation of this ambitious project is limited to the infrared range, since most of the driving scientific themes (the study of galaxies with redshift $z > 1$, imaging of circumstellar disks, ...) mostly rely on this wavelength domain. However, JWST's high sensitivity is not an advantage for such a bright target as Io, and it will not carry instrumentation suitable for study of the atmosphere, for instance, so its usefulness for Io studies is probably limited.

12.4 FUTURE SPACE MISSIONS

Visits of space vehicles into the Jovian system are unfortunately rare. The *Pioneer 10* and *11* mission vehicles were the first spacecraft to ever visit Jupiter in December 1973 and December 1974, but it was only when the spacecraft *Voyager 1* in March 1979 crossed into the Jovian moon system that the volcanic activity of Io was finally revealed (Morabito *et al.*, 1979; see also Chapter 2), opening up a completely new world for planetary scientists. The *Galileo* mission to Jupiter (Chapter 3) was conceived to follow on the study of the Jovian system. The spacecraft arrived in December 1995 and was placed into elongated orbits around Jupiter, which were designed for close-up fly-bys of the Galilean moons. Although several problems happened during the handful of fly-bys dedicated to Io, the instruments on board the spacecraft obtained unprecedented observations of Io that brought key discoveries, outlined in earlier chapters. The arrival of the *Cassini* mission in December 2000 while *Galileo* was orbiting in the inner part of the Jovian system gave a unique opportunity for multi-spacecraft observations of the Jovian system. However, *Galileo* was fundamentally limited in its ability to characterize Io's dynamic volcanism by its low data rate (i.e., many major eruptions that occurred during the mission were seen only as isolated snapshots). With the demise of the *Galileo* spacecraft in 2003, further observations of Io are restricted to telescopic observations from Earth, apart from observations that will be made from the *New Horizons* spacecraft in early 2007, during its Jupiter fly-by. Even with the fast progress made in the capabilities of ground-based instruments, long-term advances in understanding Io will require additional close-up studies by spacecraft.

12.4.1 *New Horizons* fly-by

The Pluto-bound *New Horizons* spacecraft (e.g., Stern and Spencer, 2003) will fly past Jupiter on 28 February 2007, and will obtain valuable observations of Io (Figure 12.3). Its closest approach distance of 2.2 million kilometers is over four times closer than that of *Cassini*, and its ultraviolet and near-infrared instrumentation surpasses that of both *Galileo* and *Cassini* in several respects. *New Horizons* will obtain global panchromatic imaging of Io with resolution of 20 km or better, to study surface changes since *Galileo*, though color imaging will be restricted to Jupiter-shine imaging of the Jupiter-facing hemisphere due to saturation on the dayside. Volcanic plumes will be inventoried over several orbits, providing time variability information and perhaps revealing correlations with dust streams that may be detected by the *New Horizons* dust instrument. There will also be global 0.8–2.5 μm imaging of nightside volcanic thermal emission with a spatial resolution of better than 200 km, allowing a detailed study of high-temperature volcanic thermal emission. Numerous disk integrated 500–1,800 Å spectra will document the atomic emissions from Io's atmosphere as a function of orbital and magnetospheric longitude, as well as torus emissions. Observations of several Io eclipses will document the response of the ultraviolet atmospheric emissions to eclipse, and will provide unprecedented spatial resolution on the 1.7-μm SO emissions detected in ground-based observations (de Pater *et al.*, 2002).

12.4.2 Future planned missions

Only one Jupiter mission is currently under development – the Juno Jupiter orbiter which is designed for detailed studies of Jupiter's interior, aurorae, and inner magnetosphere. Juno's studies of the Jovian plasma may illuminate some aspects of Io's interaction with the magnetosphere, but Juno will not carry instrumentation for useful observations of Io itself. Various incarnations of a Europa orbiter mission have been studied over the past decade, and such a mission is likely to carry remote-sensing instrumentation that will also provide valuable information on Io, even though

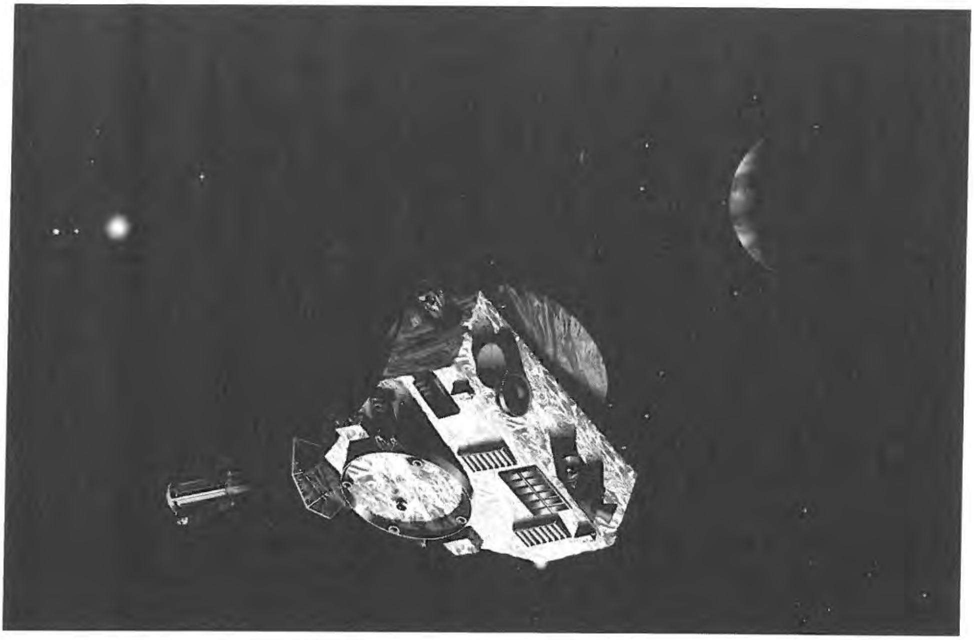

Figure 12.3. Artistic vision of the Pluto-bound *New Horizons* spacecraft flying past the Jovian system at the end of February 2007. Multi-wavelength observations (from ultraviolet to near-infrared) of Io's surface, plumes, and atmosphere will be recorded. (See also color section.)

radiation concerns would probably preclude close approaches to Io. However, until a Europa mission is funded and its payload is chosen, its potential contribution to Io science remains unknown.

12.4.3 A dedicated Io mission?

In 2001, at the request of the U.S. Office of Management and Budget, the National Academy of Sciences commissioned the National Research Council to do a study to assess the highest priority objectives in Solar System exploration for the next decade, 2003–2013. This study published in 2002 and commonly referred to as the Planetary Decadal Survey (Space Studies Board, 2003), solicited input from throughout the planetary science community and the general public. A series of white papers were submitted to the Survey Panel on many of the objects in the Solar System and why they were good candidates for future exploration (Sykes, 2002). One such paper was submitted on the future of Io exploration (Spencer *et al.*, 2002). Though an Io-dedicated spacecraft mission did not make the cut in terms of highest priority missions in the next decade (partly due to engineering and technology development issues), a future Io-dedicated mission was encouraged for the following decade (2013–2023) after certain technologies (e.g., radiation-hardened circuitry, advanced propulsion and communications) are developed for other missions. As we outlined in the Io white paper (Spencer *et al.*, 2002), we envision a Jovicentric orbiter with an eccentric orbit with a perijove near Io and an orbital period of ~1 month. Based on our experience with *Galileo*, such an orbiter could survive the heavy radiation environment near Io for 4 years or more with ~50 monthly close Io fly-bys. This would enable repeated fly-bys of specific hemispheres or regions of Io with similar lighting geometries to emphasize study of time-variable phenomena, which is necessary for studies of active volcanism. Data downlink and distant observations would occur during more distant parts of the orbit. Useful instruments to be carried on such an orbiter include: ultraviolet spectrometer for atmospheric studies, high-resolution visible camera (1–10 m per pixel local imaging, 100 m per pixel global imaging), 1–5 -μm spectrometer with 1-km resolution, 10 and 20-mm imager with 10-km resolution, laser altimeter, mass spectrometer, and fields and particles instruments (Spencer *et al.*, 2002). Furthermore, the spacecraft would ideally carry several (~3) penetrators with 20-hr or better lifetimes to perform *in situ* studies of Io's surface. These penetrators would carry seismometers to reveal Io's internal structure, mass spectrometers to determine atmospheric composition during descent, and a surface composition instrument package. More limited missions along these lines have been previously proposed to NASA's Discovery Program (i.e., small, focused planetary missions) in the late-1990s/early-2000s (e.g., Smythe *et al.*, 1998; Esper *et al.*, 2003)

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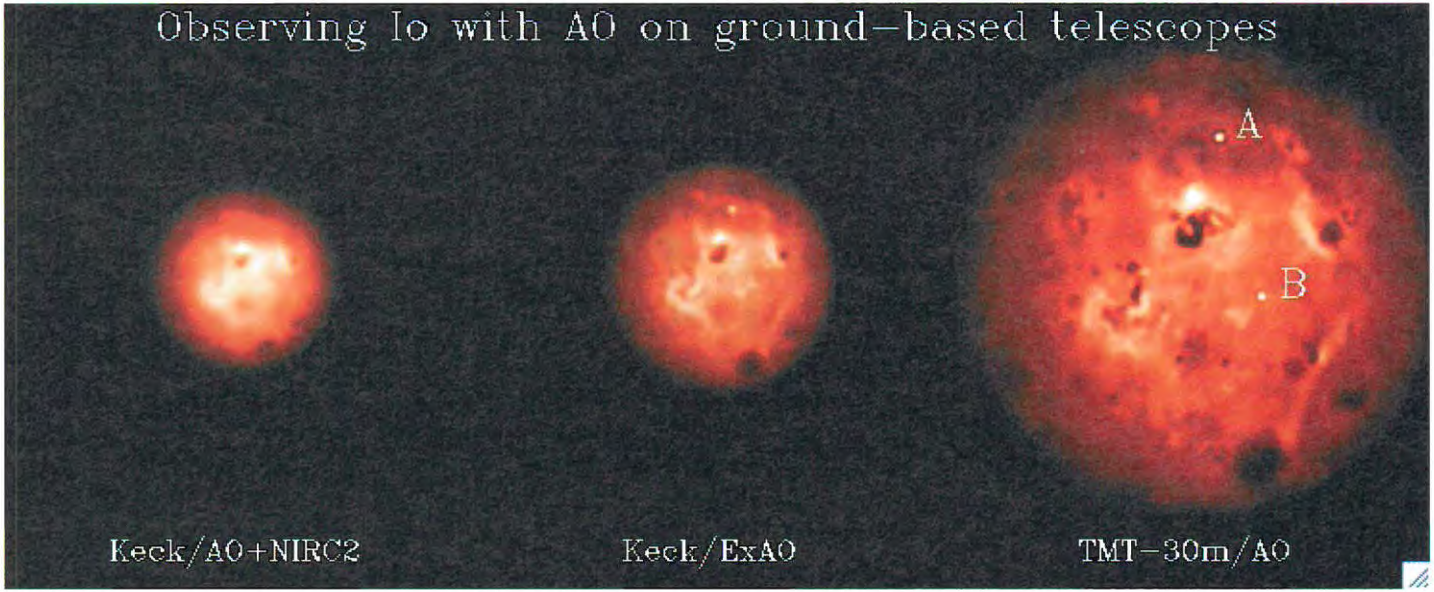

Figure 12.1. Observations of Io in H-band (1.6 μm) with several AO systems. Three AO system performances were simulated. The spatial resolution with the Keck AO is estimated to be 160 km on the center of the disk. An extreme AO system (ExAO) would provide a full correction of the wavefront for such a bright target, providing a sharper image, with a spatial resolution of 120 km on Io. Because of its larger aperture, the spatial resolution of 45 km, attainable on Io with the Thirty Meter Telescope (TMT), would be competitive with most of the global observations recorded by the *Galileo* spacecraft. On rare occasions the thermal output of hot spots is large enough at H-band to be detected in sunlit observations such as these. Thanks to the stability provided by ExAO, hot spot A is detected with this system. Hot spot B, with an intensity 12 times lower than the Keck AO limit of detection is clearly visible in the TMT simulation. More of these high-temperature eruptive centers could be studied with those new instruments helping to better constrain the composition of the magma. No *a posteriori* data processing to enhance the sharpness of the images (such as deconvolution) was applied to these simulations.

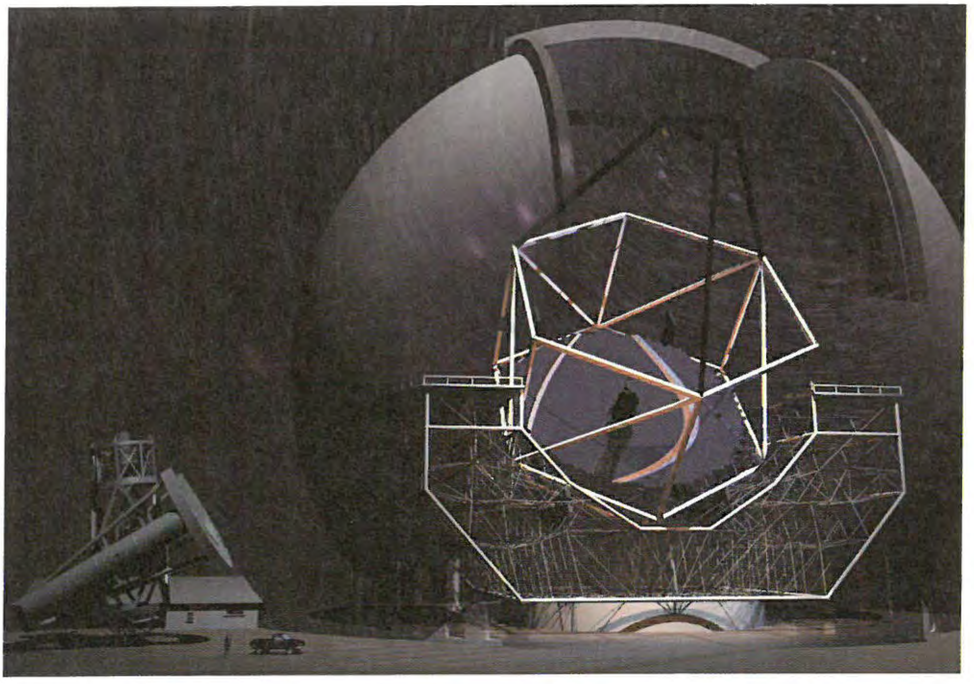

Figure 12.2. Artist's renderings of the TMT and comparison with the Palomar 5-m Hale telescope. This telescope, developed in partnership between the U.S.A. and Canadian institutes, should be available in 2014. Because of the large size of its aperture, combined with the capabilities of AO systems, it will provide an unprecedented spatial resolution of Io, better than most of the *Galileo* spacecraft infrared observations (courtesy California Institute of Technology).

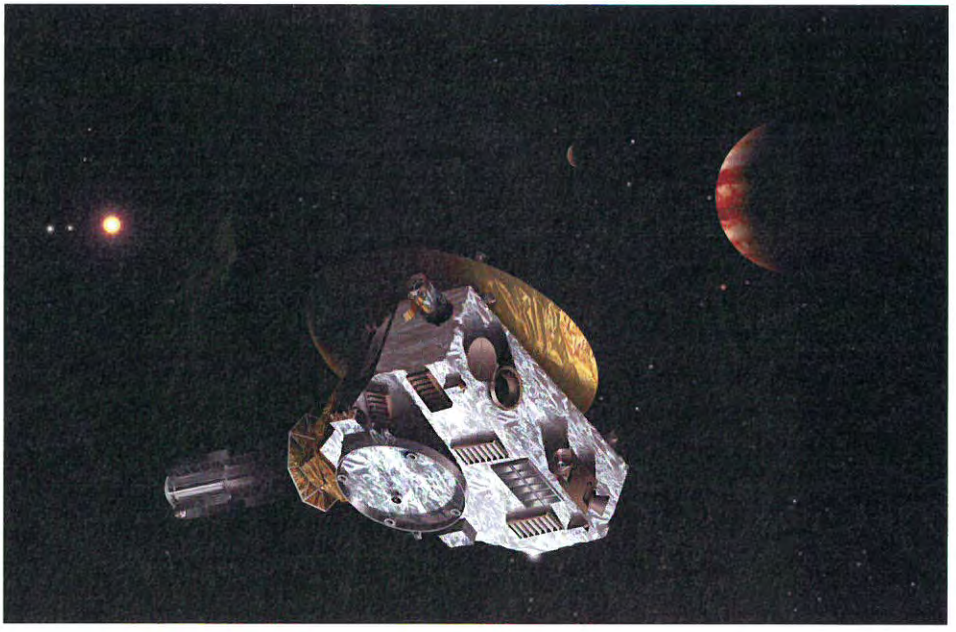

Figure 12.3. Artistic vision of the Pluto-bound *New Horizons* spacecraft flying past the Jovian system at the end of February 2007. Multi-wavelength observations (from ultraviolet to near-infrared) of Io's surface, plumes, and atmosphere will be recorded.