

# THE SCIENCE CASE FOR IO EXPLORATION

A WHITE PAPER TO THE 2023–2032 PLANETARY SCIENCE AND ASTROBIOLOGY DECADAL SURVEY



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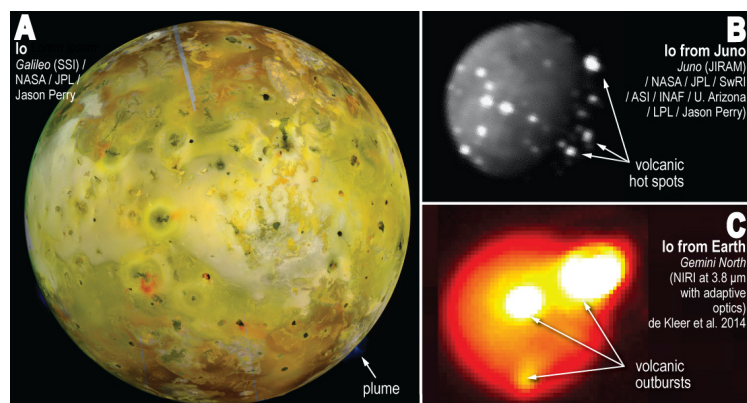


**SUMMARY:** Io is a priority destination for solar system exploration, as it is the best natural laboratory to study the intertwined processes of tidal heating, extreme volcanism, and atmosphere-magnetosphere interactions. Io exploration is relevant to understanding terrestrial planets and moons (including the early Earth), ocean worlds, and exoplanets across the cosmos.

**1. Io is a priority destination for future exploration.** Jupiter’s innermost large moon, Io, is the most geologically active world in the solar system (Fig. 1). Io’s surface is marked by hundreds of active volcanoes, erupting lava fountains, evolving sulfurous ices, enormous mountains, and deposits from towering volcanic plumes that pollute the Jovian system and feed its enormous magnetosphere. This unparalleled activity is powered by rampant tidal heating, where the gravitational interactions between Io and its neighboring moons result in time-varying tides from Jupiter that deform and heat Io’s interior. Io is the best natural laboratory to study these intertwined processes, and it is a vitally important destination for addressing high priority, cross-cutting science investigations relevant to broad swaths of planetary science—from the Hadean Earth–Moon system when life emerged, to present-day potentially habitable ocean worlds, and distant exoplanets where conditions are even more extreme. Characterization of Io will guide future observations of both ocean worlds and exoplanetary targets. In a sense, Io is the uninhabitable world that teaches us how habitable worlds form and work.

## 2. What has changed since the last decadal survey?

Since *Vision and Voyages*<sup>1</sup>, there have been many paradigm-changing advances in our understanding of Io, including (but not limited to): extremely high-resolution imaging of active volcanoes<sup>2</sup>; new insights into tidal evolution, motivated by results from *Cassini*<sup>3–9</sup>; observations of Io’s poles by *Juno*<sup>10–13</sup>; new analysis of *Galileo* magnetometer data suggesting the presence of a long-hypothesized global subsurface magma ocean on Io<sup>14</sup>, although controversial<sup>15–16</sup>; and the discovery of exoplanet analogs, including resonant “super-Ios” in TRAPPIST-1<sup>17</sup> and “lava worlds” like 55 Cnc e<sup>18</sup>. Despite these advances, there are still critical knowledge gaps requiring *in situ* geophysical and geochemical measurements, and high-resolution imaging—all beyond the capabilities of forthcoming missions to the Jupiter system—necessitating a dedicated mission to Io.



**Fig. 1:** Io is a tidally-heated wonderland—key to understanding terrestrial planets, ocean worlds, and exoplanets.

**3. The science rationale for exploring Io.** Io is a unique solar system world—lying at the nexus of a variety of high priority, cross-cutting scientific questions in planetary science. We frame the science case for Io exploration around five Cross-Cutting Themes: (1) tidal heating, (2) heat flow, (3) volcanism; (4) atmospheres, and (5) magnetospheric interactions. Table 1 lists Priority Science Questions for each Cross-Cutting Theme.

**3.1. Cross-Cutting Theme 1: Io is the best place to study tidal heating.** Tidal heating is a fundamental process for shaping planetary bodies and creating potentially habitable environments across the cosmos (see ref. 19 for a review). Tidal heating drives the orbital and

**Table 1: Cross-Cutting Themes and Priority Science Questions for Io exploration.**  
Themes and Questions are not ranked.

TIDAL HEATING	Q1.1	What is the magnitude and spatial distribution of Io's heat flow?
	Q1.2	What is the interior structure of Io, the distribution of melt, and does Io have a magma ocean?
	Q1.3	Where and how is tidal heat being dissipated in Io's interior?
	Q1.4	How do planetary materials respond to tidal forcing at relevant pressure and temperature conditions?
	Q1.5	How does Io's shape and rotation respond to tidal forces?
	Q1.6	What are the present-day orbital migration rates of the Galilean satellites, and is the system in equilibrium?
HEAT FLOW	Q2.1	How does Io lose its internal heat, and what is the balance between different heat loss mechanisms (conduction, heat-pipe volcanism, intrusions, etc.)?
	Q2.2	How do volcanic eruptions and their characteristics (temperature, composition, spatial distribution, variability, etc.) relate to Io's deep interior?
	Q2.3	What is the thickness, composition, structure, stress-state of Io's lithosphere?
	Q2.4	What is the composition and state of Io's core, and is there a core dynamo?
	Q2.5	How is heat transported through Io's deep mantle, and what is the balance between convection and advection of melt?
	Q2.6	What was Io's original volatile inventory (H <sub>2</sub> , H <sub>2</sub> O, CO <sub>2</sub> , etc.), and how were those volatiles lost?
	Q2.7	Do stable isotopes record the long-term evolution of Io?
VOLCANISM	Q3.1	What is the compositional range, chemistry, and distribution of Io's magmas, and how do these different magmas contribute to Io's heat loss and surface features?
	Q3.2	How do Io's paterae form and operate, and why are they the predominant volcanic landform?
	Q3.3	What processes create and destroy Io's mountains, and how do tectonism and magmatism interact on local and global scales?
	Q3.4	What is the extent and role of sulfur in Io's geology, and do liquid sulfur and sulfurous compounds facilitate volcanism and tectonism like water does on Earth?
	Q3.5	How do Io's plumes operate, what can they tell us about Io's interior processes, and eruptions on other airless bodies?
ATMOSPHERE	Q4.1	What are the dominant sources and sinks of Io's atmosphere, and how do they vary with time and location?
	Q4.2	What is the three-dimensional distribution, temperature, and composition of Io's atmosphere?
	Q4.3	What are the minor constituents of Io's atmosphere?
	Q4.4	What are the dynamics of Io's atmosphere and plumes?
	Q4.5	What chemical and physical processes are responsible for Io's complex surface color patterns?
	Q4.6	How do aerosols, visible in the plumes, interact with the atmosphere, surface, and broader Jupiter environment?
MAGNETOSPHERE	Q5.1	What are the velocities, fluxes, and composition of material escaping Io into the Jupiter system, and how do they vary with time and volcanic activity?
	Q5.2	How do plasma-atmosphere-ionosphere interactions around Io vary as a function of time, location, and volcanic activity?
	Q5.3	Is Io's ionosphere global, does it vary, and how is it maintained?
	Q5.4	How do magnetosphere-atmosphere electrodynamic effects alter Io's atmospheric structure?
	Q5.5	What is the strength of the internal induction signal compared to ionospheric perturbations in the fields and flows?
	Q5.6	What is the flux and composition of material from Io that reaches the surface of Europa?

rotational evolution of many star–planet and planet–satellite systems, and shapes the interior structure and geological activity of planetary bodies, including producing potentially habitable subsurface oceans on Europa, Enceladus, and other ocean worlds. Yet, despite its broad-ranging importance, there are still critical knowledge gaps in our understanding of tides. For example: Where and how is tidal heat dissipated in planetary interiors? How are subsurface oceans created and maintained? Are tidally heated systems in steady state or episodic?

Io is the most tidally deformed and heated world in the solar system, thus making it the best natural laboratory to study tidal heating. The magnitude of tidal deformation and heating within Io is at least an order-of-magnitude larger than anywhere else in the solar system, meaning that important geophysical quantities are easier to measure. For example, diurnal tides are ~100 meters high on Io, compared to ~1 meter on Enceladus<sup>20</sup>. A single, well-planned mission could characterize Io's tidal heating in a way that is simply not possible at other tidally-heated worlds where critical geophysical measurements (e.g., shape, gravity, tidal deformation, libration, obliquity, magnetic induction, etc.) are at the edge of detectability<sup>21</sup>. An Io mission could feasibly

measure all of these parameters simultaneously, and test hypotheses about tidal heating and deformation used for all ocean worlds. Io could be the Rosetta Stone to tidally deformed worlds.

To understand how and where tidal heat is dissipated, it is critically important to determine the interior structure of Io, and in particular, whether it has a present-day magma ocean (Fig. 2). A magma ocean is defined as a global, continuous subsurface melt layer<sup>19</sup>, analogous to the subsurface water oceans within many icy ocean worlds<sup>21</sup>. While there are notable petrological differences (e.g., densities of solid and melt

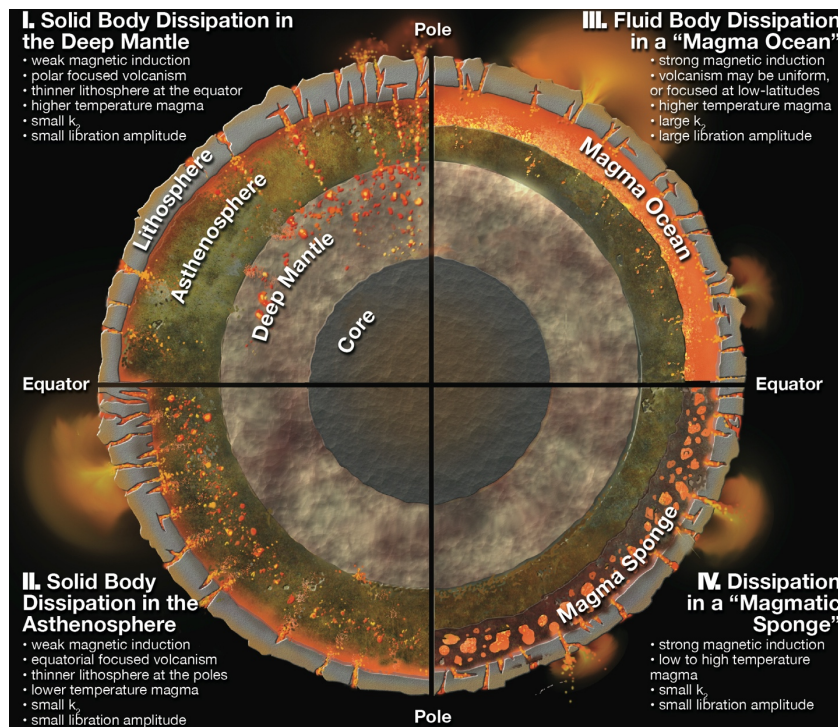


Fig. 2: Four competing models for the interior structure of Io and where tidal heat may be dissipated. Figure adapted from ref. 19.

phases), the measurements and models used to identify and characterize subsurface water and magma oceans are nearly identical. The existence of a magma ocean within Io has been long-debated, and even the best evidence (from magnetic induction) is controversial<sup>14–16</sup>. The existence of a subsurface ocean can significantly alter how tidal heat is dissipated within the interior and how that heat manifests at the surface<sup>8–9,22</sup>. If there is no ocean, dissipation occurs entirely within rock, and surface processes (e.g., volcanoes) should be well-coupled with tidal heating at depth. In contrast, if there is an ocean, dissipation could occur in both the fluid and solid layers, and the surface processes may only weakly reflect processes in the deep interior. A future Io mission could definitively test the magma ocean hypotheses using a combination of complementary geophysical measurements (e.g., gravity, libration, magnetic induction, etc.).

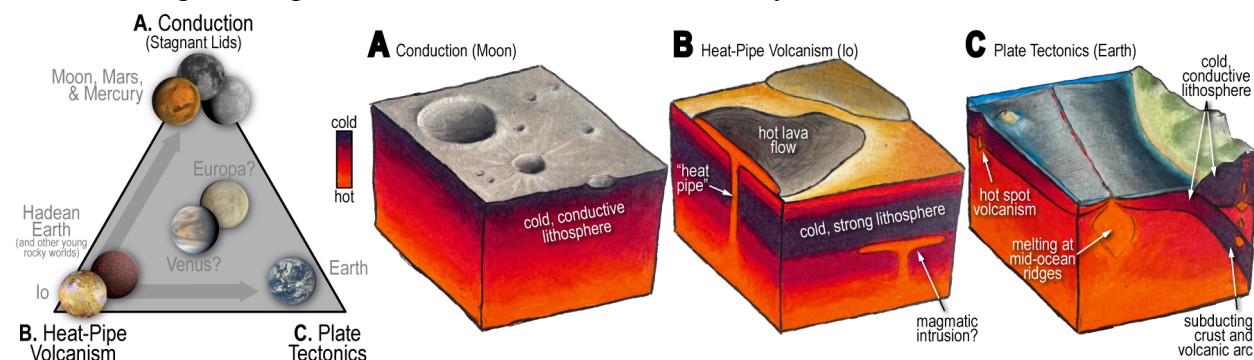
The energy driving present-day activity on Io and Europa comes from the mean motion resonance between the satellites (the Laplace resonance) which transfers Jupiter's rotational energy into the orbits and interiors of the satellites<sup>23–24</sup>. However, we do not know whether these processes are in equilibrium, or whether tidal heating and orbital migration vary episodically<sup>25–27</sup>. At present, there are significant uncertainties about Io's energy budget, both in terms of the heat coming out from volcanoes<sup>28</sup> and the heat going in from tides<sup>29</sup>. The uncertainties are too large to determine if Io is in thermal equilibrium<sup>19</sup>. This is a major problem, as our understanding of the Laplace resonance (and by extension, our understanding of subsurface oceans within Europa and Ganymede) is contingent on knowing if Io is in steady state. While *Europa Clipper* and *JUICE* will constrain dissipation within Europa and Ganymede<sup>30</sup>, observations at Io are necessary to fully solve the energy budget of the system since they are linked by the resonance.

**3.2. Cross-Cutting Theme 2: Io is the best place to study how rocky worlds respond to extreme heat flow.** Io is a body characterized by its response to the enormous amount of tidal heat dissipated within it. The average heat flow of Io is more than an order-of-magnitude



larger than Earth:  $1.5\text{--}4.0\text{ W/m}^2$  at Io<sup>31</sup> versus  $0.09\text{ W/m}^2$  at Earth<sup>32</sup>. The need to accommodate and remove this vast heat supply defies our usual models of planetary cooling, and has led to a variety of questions and hypotheses about how bodies can operate in this high internal energy state. At present, most rocky bodies in the solar system cool by conduction of heat through an ever-thickening lithosphere (**Fig. 3A**). Even the Earth, with its plate tectonics, cools primarily through conduction, with only minor contributions from advection of melt at mid-ocean ridges<sup>33</sup> (**Fig. 3C**). Io is believed to cool primarily by “heat-pipe” volcanism, whereby magma and heat are advected to the surface by volcanic processes<sup>31,34</sup> (**Fig. 3B**). Subsequent eruptions bury cold lavas into the interior where they re-melt and mix back into the system (the “crustal conveyor belt”<sup>35–37</sup>). While Io is the only heat-pipe world in the present-day solar system, it is believed that most terrestrial planets went through a similar phase early on, including the Earth<sup>38–41</sup>. Some exoplanets, particularly super-Earths, may also go through an extended heat-pipe phase<sup>40</sup>. Thus, Io is a window into the earliest, and most obscure phases of terrestrial planet formation and evolution.

Io’s extreme heat flow has shaped the composition of the body by distinct, but largely unknown mechanisms. The Galilean satellites show a systematic gradient in bulk density with distance from Jupiter, with the innermost satellites containing less ice than those farther out<sup>42</sup>. Tidal heating provides more than enough energy to remove massive volumes of ice from Io and Europa<sup>43</sup>, but how this process might have operated, and its efficiency, are currently unknown. *In situ* measurements of stable isotopes may provide a powerful method for investigating this long-term evolution, as has been demonstrated at Titan and Pluto<sup>44–49</sup>. There have been tentative detections of sulfur isotope fractionation at Io with ground-based radio observations<sup>50</sup>, although interpretation of these results is limited by our current understanding of Io’s atmosphere<sup>19</sup>. With some theoretical development, isotopic ratios have the potential to be a transformative tool for understanding the long-term evolution of Io and other tidally-heated worlds.



**Fig. 3:** Io is the archetypal “heat-pipe” world, representing a critical end-member for how planetary bodies lose internal heat. The Earth and other terrestrial planets likely went through a heat-pipe phase early in their histories.

**3.3. Cross-Cutting Theme 3: Io is the best place to study extreme volcanism.** Io is host to a stunning range of volcanic morphologies and eruptions, providing an unparalleled opportunity to investigate fundamental volcanic processes relevant to worlds across the solar system and beyond. Besides Earth, Io is the only other body to display unquestionably active silicate volcanism, seemingly for the duration of modern observation<sup>51–52</sup>. At any given time, 50–100 Ionian volcanoes are erupting, resurfacing the moon at a rate of  $\sim 1\text{ cm/year}$ —equivalent to the whole moon turning over  $\sim 40$  times in  $4.5\text{ Ga}$ <sup>53–56</sup>.

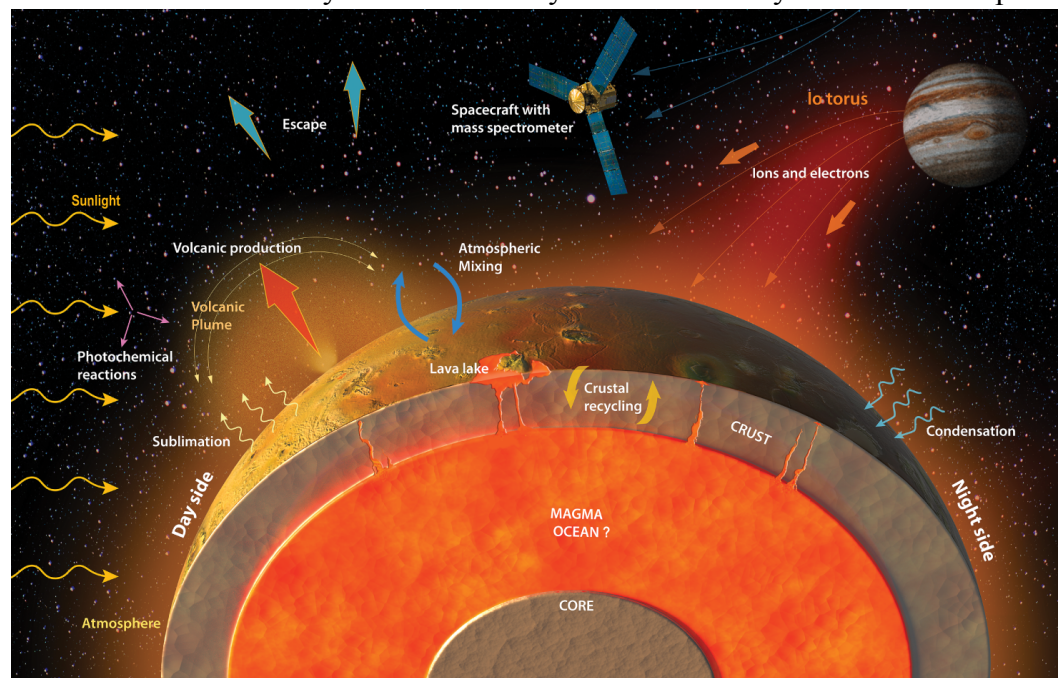
The largest active lava flow fields on Io are hundreds of kilometers long, and are more akin to the mare flood basalts that dominate the nearside of the Moon, or lava flows within terrestrial Large Igneous Provinces (LIPs) and continental flood basalt provinces which (fortunately) are not

active today<sup>57–58</sup>. LIPs have been implicated in several mass extinction events, including the Permian–Triassic extinction<sup>59</sup>. The formation process for these large, expansive flows is poorly understood: are they emplaced rapidly in open channels or sheets<sup>60–61</sup>, or more slowly in insulated tubes and flows<sup>62</sup>? Io is the ideal environment for studying flow emplacement and the influence of other factors such as topography and flow viscosity.

There is evidence that Io hosts active ultramafic volcanism<sup>63–65</sup>. Ultramafic volcanism last occurred on the Earth during the Archean and Proterozoic, and in similarly ancient terrains on Mercury, Moon, and Mars<sup>66–67</sup>. There are many unresolved questions about how these hot (1600–1640°C), low viscosity, mantle-derived melts are transported to the surface and emplaced. Io is the only place in the solar system where we can study these processes in action. Observations of Io’s ultramafic lavas, coupled with laboratory experiments on analog materials, can provide key insights into the chemistry of the mantle from which they are sourced.

Io produces massive explosive eruptions, manifested as outbursts and plumes that expel gas and dust several hundreds of kilometers above the surface. Volcanic plumes provide a unique view into the interior structure and geology of a variety of worlds—from Io, to Europa, Enceladus, Triton, Mercury, Moon, and Earth<sup>51,68–72</sup>. Plumes provide critical information about the volatile content, composition of mantle sources, and conduit geometry. Io’s plumes are frequently invoked as a theoretical model for ancient explosive eruptions on the Moon<sup>73–75</sup> and Mercury<sup>76</sup>, and these models are often used to infer volatile content<sup>76–78</sup>. *In situ* measurements of gas species and fractionation in an active Ionian eruption could be used to both improve our understanding of Io’s interior, and to benchmark models used for eruptions on other worlds.

**3.4. Cross-Cutting Theme 4: Io’s dynamic atmosphere is unlike any other.** Io’s tenuous, yet collisional, atmosphere is unique in the solar system (Fig. 4; see ref. 79 for a review). Like many aspects of Io, the atmosphere is a byproduct of extreme tidal evolution and volcanism—and is therefore a key record of the interior chemical evolution of Io. Io’s predominantly SO<sub>2</sub> atmosphere is supported by both volcanism and sublimation of SO<sub>2</sub> surface ices, although the exact mechanisms and balance between these sources are still fiercely debated<sup>80–92</sup>. At times, the observational evidences yield contradictory answers<sup>91</sup>. Analysis of Io’s atmosphere is complicated



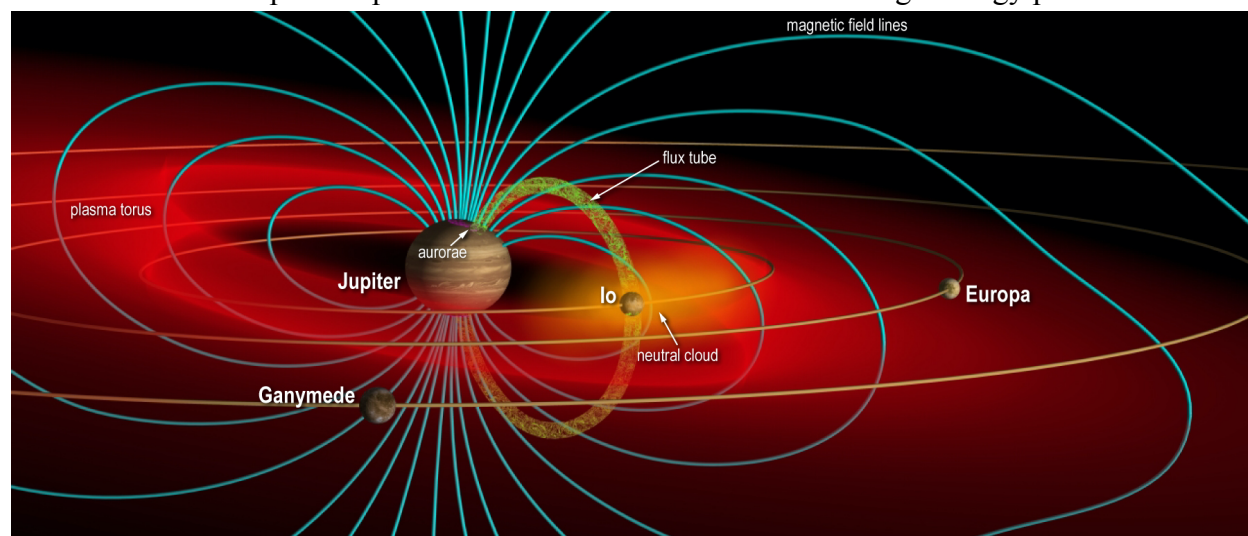
**Fig. 4:** Schematic diagram of Io’s dynamic atmosphere, its sources and sinks, and the processes affecting the chemical and isotopic distributions on and around Io. Figure adapted from ref. 19.



as the atmosphere varies wildly on both spatial and temporal scales. Atmospheric density varies by six orders of magnitude likely due to the extreme range of surface temperatures (e.g., day, night, eclipse, volcanic hotspots). This set of conditions results in a temperature-pressure regime unlike any other known atmosphere in the solar system. Pressure differentials arising from sublimation, condensation, and collapse of volcanic plumes drive horizontal winds reaching hundreds of meters per second that then interact in complex ways with Io's sublimation-driven atmosphere<sup>93–95</sup>. The plumes themselves are initiated by unknown processes, plausibly including magmatic extrusions, intrusions, sublimation of volatiles, plasma processes, etc. Unlike other atmospheres, Io's position within the Jovian magnetosphere leads to a variety of non-thermal processes involving charged particles that affect the surface and atmosphere<sup>96</sup>. Ultimately, Io's atmosphere feeds the Io torus and contaminates the surfaces of the other moons. It is important to fully characterize Io's atmosphere in order to understand what materials are transferred between the moons. Io's atmosphere challenges our understanding of atmospheric physics, chemistry, dynamics, and atmosphere-magnetosphere interactions. Exploration of Io will therefore ultimately extend our knowledge of these processes. Moreover, while Io's atmosphere is unique in the solar system, it is a vitally important analog for many exoplanets, including tidally-locked exoplanets orbiting magnetically active M-dwarf stars<sup>18</sup>.

### **3.5. Cross-cutting theme 5: Io is the driver of magnetospheric activity in the Jovian system.**

The extreme volcanic activity of Io supplies the Jovian magnetosphere with neutral gas, plasma, and dust (**Fig. 5**; see ref. 96 for a review). Approximately 1 ton/second of material is stripped from Io's atmosphere, forming neutral clouds that become ionized and picked up by Jupiter's strong magnetic field. As this plasma moves out into the vast magnetosphere (>1,000 times the size of the Sun) it is heated by a variety of processes, accelerating some particles up to 99.999% the speed of light<sup>97</sup> creating the hazardous radiation environment that threatens spacecraft in the system. Charged particles are also accelerated along the magnetic field and into Jupiter creating the most powerful electrodynamic satellite-planet connection in the solar system, as indicated by Io's permanent, bright auroral footprint on Jupiter's poles. These particles also impact and alter the surfaces of the other Galilean satellites, creating their sputtered atmospheres<sup>98</sup>, and altering surface crystallinity, thermal inertia, and chemistry<sup>99</sup>. Understanding these processes is crucial to determine how radiation affects the potential habitability of Europa; it may inhibit<sup>100</sup> or sustain<sup>101–102</sup> life. Jupiter's space environment is a veritable zoo of high-energy processes that are



**Fig. 5: Io's volcanism shapes the Jovian space environment. Graphic by J.R. Spencer.**

relevant to many other worlds, including the Earth, other gas giant systems, exoplanets, and brown dwarfs<sup>103</sup>. As noted in the most recent heliophysics decadal survey<sup>104</sup>, Io is a prime destination for addressing its key science goals, including understanding coupling between magnetospheres, ionospheres, and thermospheres.

At the core of this activity is a complex feedback loop between Io's atmosphere and the surrounding plasma environment. Magnetospheric plasma impacts Io's atmosphere, producing a cloud of escaping neutral atoms that populate a substantial fraction of its orbit (the Io neutral cloud). These atoms are subsequently ionized by electron impacts and charge exchange, creating the dense magnetospheric plasma in Io's orbit (the Io plasma torus). While recent observations from *Juno*, *Hisaki*, and ground-based observations provide some information about this complicated feedback, the details and overall stability of this process are uncertain<sup>96,105</sup>. The role of volcanism in this feedback loop is poorly understood, as limited temporal coverage has made it difficult to unambiguously link specific eruptions with subsequent changes in the magnetosphere<sup>106</sup>. Despite the complexity, there is hope for separating out these different processes—in part because they operate on different timescales: plasma takes minutes to pass Io; neutrals survive in Jupiter orbit for hours; plasma takes days to move through the Jovian system. This separability, coupled with *in situ* measurements and models, could enable significant advances in our understanding of plasma–atmosphere interactions and mass loss processes both at Io and for a variety of solar system worlds and exoplanets.

**CONCLUSION: We recommend that the decadal survey consider Io as a critical, scientifically meritorious destination for future exploration. The scope and importance of science questions at Io necessitates a broad portfolio of research and analysis, telescopic observations, and planetary missions—including a dedicated, New Frontiers class Io mission<sup>107</sup>.**

<sup>1</sup>Vision and Voyages (10.17226/13117); <sup>2</sup>de Kleer et al. 2017 (10.1038/nature22339); <sup>3</sup>Lainey et al. 2009 (10.1038/nature08108); <sup>4</sup>Lainey et al. 2012 (10.1088/0004-637X/752/1/14); <sup>5</sup>Lainey et al. 2017 (10.1016/j.icarus.2016.07.014); <sup>6</sup>Fuller et al. 2016 (10.1093/mnras/stw609); <sup>7</sup>Beuthe 2013 (10.1016/j.icarus.2012.11.020); <sup>8</sup>Tyler et al. 2015 (10.1088/0067-0049/218/2/22); <sup>9</sup>Hay & Matsuyama 2019 (10.1016/j.icarus.2018.09.019); <sup>10</sup>Bolton et al. 2017 (10.1126/science.aal2108); <sup>11</sup>Connerney et al. 2017 (10.1002/2018GL077312); <sup>12</sup>Mura et al. 2018 (10.1126/science.aat1450); <sup>13</sup>Mura et al. 2020 (10.1016/j.icarus.2019.113607); <sup>14</sup>Khurana et al. 2022 (10.1126/science.1201425); <sup>15</sup>Roth et al. 2017 (10.1002/2016JA023701); <sup>16</sup>Blöcker et al. 2018 (10.1029/2018JA025747); <sup>17</sup>Barr et al. 2018 (10.1051/0004-6361/201731992); <sup>18</sup>Henning et al. 2018 (arXiv:1804.05110); <sup>19</sup>de Kleer et al. 2019c (https://www.kiss.caltech.edu/final\_reports/Tidal\_Heating\_final\_report.pdf); <sup>20</sup>Burns & Matthews 1986 (1986sate.conf...B); <sup>21</sup>Nimmo & Pappalardo 2016 (10.1002/2016JE005081); <sup>22</sup>Beuthe 2016 (10.1016/j.icarus.2016.08.009); <sup>23</sup>Peale et al. 1979 (10.1126/science.203.4383.892); <sup>24</sup>Murray & Dermott 1999 (10.1017/CBO9781139174817); <sup>25</sup>Ojakangas & Stevenson 1986 (10.1016/0019-1035(86)90163-6); <sup>26</sup>Hussman & Spohn 2004 (10.1016/j.icarus.2004.05.020); <sup>27</sup>Shoji et al. 2014 (10.1016/j.icarus.2014.03.006); <sup>28</sup>Veeder et al. 1994 (10.1029/94JE00637); <sup>29</sup>Lainey et al. 2009 (10.1038/nature08108); <sup>30</sup>Dirkx et al. 2017 (10.1016/j.pss.2016.10.011); <sup>31</sup>Moore et al. 2007 (10.1007/978-3-540-48841-5\_5); <sup>32</sup>Turcotte & Schubert 2002 (10.1017/S0016756802217239); <sup>33</sup>Jaupart et al. 2015 (10.1016/B978-0-444-53802-4.00126-3); <sup>34</sup>O'Reilly & Davies 1981 (10.1029/GL008i004p00313); 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