Ariel’s Elastic Thicknesses and Heat Fluxes

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Abstract

The surface of Ariel displays regions that were resurfaced in the geologically recent past. Some of these regions include large chasmata that exhibit evidence for flexure. To estimate Ariel’s heat fluxes, we analyzed flexure associated with the Pixie Group of chasmata, including Pixie, Kewpie, Brownie, Kra, Sylph, and an unnamed chasma, and the Kachina Group of chasmata, which includes Kachina Chasmata. We analyzed topography of these chasmata using digital elevation models developed for this work. Our results indicate that Ariel’s elastic thicknesses range between 4.4 ± 0.7 km and 11.4 ± 1.4 km across the imaged surface. The younger Kachina Group has a relatively low elastic thickness of 4.4 ± 0.7 km compared to most chasmata in the older Pixie Group (4.1 ± 0.3 km to 11.4 ± 1.4 km). A pure H2O ice lithosphere would correspond to heat fluxes ranging from 17 to 46 mW m−2 for the Kachina Group and from 6 to 40 mW m−2 for the Pixie Group. Alternatively, if NH3 hydrates are present in Ariel’s lithosphere, then the estimated heat fluxes are lower, ranging from 3 to 18 mW m−2 for the Kachina Group and from 1 to 16 mW m−2 for the Pixie Group. These results indicate that accounting for NH3 hydrates in the lithosphere substantially alters the resulting heat flux estimates, which could have important implications for understanding the lithospheric properties of other icy bodies where NH3-bearing species are expected to be present in their lithospheres. Our results are consistent with Ariel experiencing tidal heating generated from mean motion resonances with neighboring satellites in the past, in particular Titan and Miranda.

Unified Astronomy Thesaurus concepts: Uranian satellites (1750); Tectonics (2175); Natural satellites (Solar system) (1089); Natural satellite surfaces (2208); Planetary science (1255)

Supporting material: data behind figure

1. Introduction

1.1. Ariel’s Geology

The Uranian satellite Ariel has likely experienced an eventful and long-lasting tectonic history. The section of Ariel’s surface imaged by Voyager 2 is dominated by sets of large canyons, termed chasmata, bounded by extensional normal faults (Figures 1(a), (b); Smith et al. 1986; Plescia 1987; Croft & Soderblom 1991; Schenk & Moore 2020; Beddingfield & Cartwright 2021). Some of Ariel’s chasmata are 3–4 km in depth (Thomas 1988) and hundreds of kilometers in length. Some of the chasmata have smooth floors with topographically depressed medial grooves flanked by elevated parallel ridges, forming double-ridge morphologies (Figure 1(c)) (Schenk 1991; Beddingfield & Cartwright 2021) that are reminiscent of double ridges on Europa (e.g., Pappalardo et al. 1999; Nimmo et al. 2003; Leonard et al. 2018) and Triton (Prockter et al. 2005). Ariel’s double ridges may have formed from a combination of tectonic and cryovolcanic activity (e.g., Smith et al. 1986; Schenk 1991; Beddingfield & Cartwright 2021). Landslide deposits and fresh crater ejecta are also present in some locations within Ariel’s chasmata (e.g., Croft & Soderblom 1991).

Based on their relative ages, Ariel’s chasmata have been separated into the older Pixie Group and the younger Kachina Group. Age estimates are based on the degradation states of the fault scarps, the densities of impact craters overprinting these scarps, and cross-cutting relationships between these faults and geologic units (Croft & Soderblom 1991). The Pixie Group includes Brownie, Kewpie, Pixie, Sylph, Korrigan, and Kra Chasmata (Figure 1(a)). The Kachina Group is made up of the faults comprising Kachina Chasmata (Figure 1(b)). As summarized in Croft & Soderblom (1991), the fault scarps within the Kachina Group are not visibly overprinted by any obvious impact craters. Additionally, the normal fault scarps that make up the Kachina Group appear sharp and angular, supporting the interpretation that they are younger than the chasmata within the Pixie Group.

The small canyon called Kra Chasma appears to have been offset in two places (Kargel 1988), creating two small unnamed canyons (Figure 1(a)). As summarized in Kargel (1988), sections of Ariel’s older and more heavily cratered surface may have experienced translational motion, resulting in rafting of large blocks. Rafting may have occurred as Ariel’s chasmata spread apart, perhaps analogous to seafloor spreading on Earth (Croft & Soderblom 1991).

Ariel’s surface can be separated into four broad geologic units: ancient, cratered plains that represent the oldest terrain on Ariel and are thought to be 1.3 (−0.6/+2.0) Ga (Kirchoff et al. 2022), and three younger, “smooth materials” units that are subdivided based on their relative ages (Smith et al. 1986; Jankowski & Squyres 1988; see Figure 2). The Pixie Group is mostly found within the “intermediate-age smooth materials” unit, and the Kachina Group is in the “cratered plains” unit. Ariel’s tectonized region near the south pole, including the area between the Kachina Group and Pixie Group, is estimated to be 0.8 (−0.5/+1.8) Ga based on impact crater densities (Kirchoff et al. 2022). However,
it is unknown what the difference in ages is between the Kachina Group and the Pixie Group.

1.2. Ariel’s Surface Composition

Near-infrared, ground-based telescope observations indicate that Ariel’s surface is mostly composed of H2O ice mixed with dark material that is likely carbonaceous (e.g., Cruikshank 1980; Brown & Cruikshank 1983; Cartwright et al. 2018). Large amounts of CO2 ice are also present on Ariel’s trailing hemisphere and are likely generated by irradiation of H2O ice mixed with carbonaceous material on the surface (Grundy et al. 2003, 2006; Cartwright et al. 2015, 2022). Some reflectance spectra collected with ground-based telescopes also display subtle 2.2 μm absorption features that are consistent with NH3-bearing and/or NH4-bearing constituents (Cartwright et al. 2018; Cook et al. 2018; Cartwright et al. 2020). NH3 is an efficient antifreeze agent, which should allow potential liquid H2O-NH3-rich subsurface oceans to persist for longer periods of time, and at lower temperatures, compared to “pure” liquid H2O oceans (e.g., Nimmo & Pappalardo 2016). NH3-rich material originating from such a subsurface ocean could have been incorporated into cryovolcanic flows that were emplaced on Ariel’s surface. Alternatively, subsurface material rich in NH3 could have been exposed by tectonic processes, mass wasting, and impact events (Cartwright et al. 2020). NH3 is thought to be present in larger abundances in Ariel’s interior, as it was likely one of the primary constituents of the satellitesimals that accreted into Ariel and the other Uranian moons (e.g., Lewis 1972; Prinn & Fegley 1989).

The timescales over which the spectral signature of NH3-bearing material could persist on Ariel’s surface are uncertain. NH3-rich deposits exposed on Ariel and the other Uranian moons could be efficiently removed over short timescales by magnetospheric charged particle bombardment (in as little as 106 yr for Miranda; Moore et al. 2007). However, some of the NH3 molecules fragmented by irradiation should recombine to reform NH3 (e.g., Cruikshank et al. 2019), enhancing the longevity of this constituent. Furthermore, radiolytic modification of NH3 mixed with H2O ice and C-rich species likely forms new, more refractory constituents that also exhibit 2.2 μm absorption features (e.g., Allamandola et al. 1988).

1.3. Korrigan Chasma Heat Flux

Prior work has estimated heat fluxes on Ariel at the location of Korrigan Chasma (Peterson et al. 2015). Korrigan is part of the relatively old Pixie Group of canyons. Peterson et al. (2015) estimated that the lithospheric thickness in the region of

Figure 1. The large chasmata on Ariel. (a) The Pixie Group (cyan and orange arrows), which is the older set of canyons, relative to the Kachina Group (Voyager ISS image c2684535). The Pixie Group includes Brownie, Kewpie, Pixie, Slyph, Korrigan, and Kra Chasmata. Additionally, the Pixie Group includes separated canyons that may have originally aligned with Kra Chasma (orange arrows), which may have been offset due to rafting of large blocks (Croft & Soderblom 1991). (b) The Kachina Group (cyan arrows), which is likely younger than the chasmata within the Pixie Group. The Kachina Group is made up of faults comprising Kachina Chasmata and nearby subparallel faults (Voyager ISS image c2684533). (c) Double ridges (cyan arrows) present near the center of smooth floored chasmata in the Pixie Group (Voyager ISS image c2684539).
Korrigan Chasma is 3.8–4.4 km, with heat fluxes ranging between 28 and 92 mW m⁻². As summarized in Peterson et al. (2015), neither current tidal heating of Ariel, nor radiogenic heat production, nor past resonances, nor a combination of these (up to 12 mW m⁻²) are sufficient to cause these high heat fluxes, suggesting that an unknown heating event contributed to Ariel’s heat flux in this location.

In this work, we estimated the heat fluxes of Ariel across the rest of the imaged surface using flexural modeling. We analyzed chasmata (Figure 3) in the Pixie Group and have identified flexural uplift along the large chasma walls that include Kewpie, Brownie, Kra, Pixie, Sylph, and an unnamed chasma (Figure 4). We also investigated the relatively young Kachina Chasmata, which could reflect a more recent view of Ariel’s heat flux. Therefore, we measured and analyzed flexure for seven different chasmata (nine total locations), which we used to estimate heat fluxes across Ariel’s imaged surface. These nine locations may express different heating events that have occurred during Ariel’s geologic history.

Figure 2. Annotated version of the geologic map of Ariel’s imaged southern hemisphere (Croft & Soderblom 1991). The locations of the DEMs (cyan boxes) created for this study, covering the large chasmata, are shown.

Figure 3. Diagram interpretation of chasma morphology, consisting of two bounding normal faults with evidence for flexure in the form of raised rims exterior to the faults and chasma. The flexural troughs bounding the chasma (gray shaded area) are shown. The orange arrows represent the directions of displacement.
2. Methods

2.1. Digital Elevation Models

To investigate the geometries of Ariel’s chasmata, we generated digital elevation models (DEMs) using Voyager 2 Imaging Science Subsystem (ISS) images that cover these features and the surrounding terrains (Figures 2, 4(c), 5(c), 6(c)). The DEMs were generated with the Ames Stereo Pipeline (ASP) software (Broxton & Edwards 2008; Moratto et al. 2010). We used stereographic projections for the DEMs, with coordinates centered on the chasmata. Images from the ISS camera on board the Voyager 2 spacecraft were processed and map-projected using the Integrated Software for Imagers and Spectrometers (ISIS; Anderson et al. 2004). We followed the steps to preprocess Voyager 2 ISS images for input into ASP outlined in previous work (Beddingfield et al. 2015a, 2015b; Beddingfield & Cartwright 2021). To generate the DEMs used for this study, we used photoclinometry (PC), also called shape from shading, techniques (Alexandrov & Beyer 2018). See Section A.1 in the Appendix for additional details. Because the widths of the terrains that have undergone flexure are on the order of tens of kilometers, the resolutions of the available Voyager 2 ISS images (995 to 1300 m pixel\(^{-1}\)) do not affect the results of our analyses.

2.2. Elastic Thickness and Heat Flux

We used flexural modeling to estimate elastic thicknesses for each of the chasmata, utilizing a similar technique to other studies that have investigated lithospheric flexure of geologic features on icy bodies (e.g., Ruiz 2005; Giese et al. 2007). Analysis of our DEMs showed that the seven chasmata exhibit raised rims, which is an indicator of lithospheric flexure (e.g., McNutt 1984). We used the flexural curvature of the seven chasmata (Figure 7) to estimate the thicknesses of the elastic and mechanical layers beneath each of them. These thickness estimates were then used to estimate lithospheric heat fluxes in those locations.

The elastic layer of a planetary body is thinner than its more rigid mechanical layer, which supports loads over geologic timescales. As summarized in McNutt (1984), the bending moment of the elastic layer is given by

\[
M = \frac{EK_{\text{max}}T_e^3}{12(1 - \nu^2)},
\]

where \(E\) is Young’s modulus, which is almost equivalent for NH₃ hydrates and pure H₂O at cryogenic temperatures (Lorenz & Shandera 2001); \(K_{\text{max}}\) is the maximum curvature of the topography; \(T_e\) is the effective elastic thickness; and \(\nu\) is Poisson’s ratio. The bending moment of the elastic layer is equivalent to the bending moment of the mechanical lithosphere, which is given by

\[
M = \int_0^{T_e} \sigma(z)(z - z_n) \, dz,
\]
where $T_m$ is the mechanical thickness of the lithosphere; $\sigma(z)$ is fiber stress, which is the differential stress at depth $z$; and $z_n$ is the depth to the neutral stress plane, where $\sigma(z) = 0$. As summarized in McNutt (1984), the fiber stress is given by

$$\sigma_z = \frac{E}{1 - \nu^2} \frac{K(z - z_n)}{1 - \nu^2}$$

and is imposed at the condition of zero net axial force, where

$$\int_0^{T_m} \sigma(z) \, dz = 0. \quad (4)$$

Because the bending moment of the elastic layer is the same as the bending moment of the mechanical layer, the effective elastic thickness is given by

$$T_e = \left[ \frac{12 (1 - \nu^2)}{E \kappa_{\text{max}}} \int_0^{T_m} \sigma(z)(z - z_n) \, dz \right]^{1/2}. \quad (5)$$

The temperature at the base of the elastic lithosphere is given by

$$T_b = \frac{1}{\kappa} \left[ \ln \left( \frac{3D_b \mu a^4}{\varepsilon \sigma a^*} \right) \right]^{1/1}. \quad (6)$$
where $Q_a$ is the activation energy for creep, $n$ is the stress exponent, $R = 8.3145 \text{ J mol}^{-1} \text{ K}^{-1}$ is the gas constant, $D_e$ is the Deborah number, $\mu$ is the shear modulus, $A$ is the material parameter, $\dot{\varepsilon}$ is strain rate, $d$ is the grain size, and $p$ is grain size exponent (see Table 1 for values used and references). We considered strain rate values ranging from $10^{-17} \text{ s}^{-1}$, assuming features formed in 1 Ga, to $10^{-14} \text{ s}^{-1}$, assuming features formed in 1 Ma, which are possible values for icy satellites (Giese et al. 2007; Hammond et al. 2013; Peterson et al. 2015). We incorporated grain sizes ranging from 0.1 to 1 mm in diameter, based on estimated grain sizes of Europa’s lithosphere and sizes predicted for evolved ice shells (Geissler et al. 1998; Ruiz 2005; Barr & McKinnon 2007). In this range of grain sizes, superplastic flow is the dominant creep mechanism (e.g., Durham & Stern 2001).

From these equations, the thermal gradient can be calculated where

$$\Delta T = \frac{T_b - T_s}{T_e}, \quad (7)$$

and $T_s$ is the temperature at the surface. The associated heat flux can be calculated where

$$F = k_c \frac{T_b - T_s}{T_e}, \quad (8)$$

and where $k_c$ is the thermal conductivity. We utilized the $k_c$ values for both NH$_3$ hydrates mixed with H$_2$O ice and pure H$_2$O ice. We provide a summary of the values used for each parameter in Table 1 with the associated references.

As summarized in Durham et al. (2005), ice porosities may be present in the lithosphere, where the pressure is less than 1 MPa. However, the porosity of ice within the lithospheres of large icy satellites decreases with depth owing to increasing pressures (e.g., Giese et al. 2007), and it has a minimal effect on the heat fluxes obtained for Ariel (diameter = 1158 km). We therefore disregarded the effect of porosity in these calculations. However, if the lithosphere of Ariel was porous at the time that flexure took place, then the thermal conductivity, and therefore heat fluxes, would be lower.

3. Results

The elastic thicknesses of Ariel range between 4.4 $\pm$ 0.7 km and 11.4 $\pm$ 1.4 km in the nine study locations (Figure 8, Table 2). The region north of the Kachina Group, which has been interpreted to be the youngest set of faults observed on Ariel, has a relatively low elastic thickness of 4.4 $\pm$ 0.7 km. In the region of the Pixie Group, elastic thickness values range from 4.1 $\pm$ 0.3 km to 11.4 $\pm$ 1.4 km. Our results indicate that Ariel’s lithosphere has relatively higher elastic thicknesses in the regions around Brownie Chasma (10.3 $\pm$ 3.0 km), south of Pixie Chasma (9.7 $\pm$ 1.3 km), and south of Sylph Chasma (11.4 $\pm$ 1.4 km). The central region of the Pixie Group exhibits evidence for a thinner elastic layer, including the Unnamed Canyon (5.7 $\pm$ 1.0 km), Kewpie Chasma (5.3 $\pm$ 0.6 km), and Korrigan Chasma (4.1 $\pm$ 0.3 km; estimated by Peterson et al. 2015).
If pure H₂O ice is assumed for Ariel’s lithosphere (with thermal conductivity, k, of 5 W m⁻¹ K⁻¹), then the resulting heat fluxes range from 17 to 46 mW m⁻² for the Kachina Group and from 6 to 40 mW m⁻² for the Pixie Group (Figure 9). Previous work defined a heat flux range of 28–92 mW m⁻² for Korrigan Chasma, which is near the center of the Pixie Group (Peterson et al. 2015).

In contrast to our heat flux estimates assuming a pure H₂O lithosphere, our results show that if Ariel’s lithosphere is instead composed of H₂O ice mixed with small amounts of NH₃ hydrates (k, of 1–2 W m⁻¹ K⁻¹), then the estimated heat fluxes are lower, ranging from 3 to 18 mW m⁻² for the Kachina Group and from 1 to 16 mW m⁻² for the Pixie Group (Tables 2 and A1).

4. Discussion

4.1. The Effect of Lithosphere Composition

The range of heat flux estimates presented here and including the results from Peterson et al. (2015), assuming that Ariel has a pure H₂O ice lithosphere, range between 6 and 92 mW m⁻². These heat fluxes are higher than the expected heat fluxes from the mean motion resonances (MMRs) shared previously between Ariel and its neighboring satellites: 5:3 Miranda-Ariel (2.7 mW m⁻²), 2:1 Ariel-Umbriel (0.6 mW m⁻²), and 4:1 Ariel-Titania (4.3 mW m⁻²) (Tittemore & Wisdom 1990; Peterson et al. 2015; Ćuk et al. 2020). Combining the highest expected heat flux, from the 4:1 Ariel-Titania MMR, with the heat flux from radioactive decay through an H₂O ice lithosphere brings the total expected heat flux to ~12 mW m⁻² (Peterson et al. 2015), which overlaps the lower range of some of our estimated heat fluxes (Figure 9).

In contrast, the presence of small amounts of NH₃ hydrates in Ariel’s lithosphere, along with H₂O ice, substantially lowers our heat flux estimates (1–16 mW m⁻²). Because a pure H₂O ice lithosphere was assumed in prior estimations of the heat fluxes from radioactive decay and tidal heating from resonances, we did not directly compare our heat flux estimates to the expected heat fluxes from these sources for a lithosphere that includes NH₃ hydrates. However, we would expect the presence of NH₃ hydrates in the lithosphere to decrease Ariel’s bulk density. As a result, Ariel’s lithosphere may contain a higher wt% of silicate rock and radioactive elements than previously assumed (Hussmann et al. 2010), thereby enhancing internal heating. Therefore, Ariel may have higher amounts of radioactive elements than previously thought, and therefore more energy to cause resurfacing. However, additional studies are needed to fully investigate the effect that NH₃ hydrates would have on radioactive heating, the rigidity of Ariel’s lithosphere, the k₂ Love number, and the energy from tidal heating.

Other constituents that might be present in the lithosphere of Ariel, such as carbonates, organics, and phyllosilicates, could...
Table 1
Values Used for Each Parameter to Estimate Elastic Thicknesses and Heat Fluxes on Ariel

| Parameter | Value(s) Used | Reference(s) |
|-----------|---------------|---------------|
| $E$       | 9 GPa         | Gammon et al. (1983) |
| $\nu$     | 0.33          | Gammon et al. (1983) |
| $Q_s$     | 49            | Goldsby & Kohlstedt (2001) |
| $n$       | 1.8           | Goldsby & Kohlstedt (2001) |
| $p$       | 1.4           | Goldsby & Kohlstedt (2001) |
| $\rho$    | 8.314 5       | Goldsby & Kohlstedt (2001) |
| $\sigma$  | J K$^{-1}$ mol$^{-1}$ | Mancktelow (1999) |
| $D_r$     | 0.01          | Mancktelow (1999) |
| $\mu$     | 3 GPa         | Goldsby & Kohlstedt (2001) |
| $A$       | $3.9 \times 10^{-3}$ | Goldsby & Kohlstedt (2001) |
| $T_s$     | 75 K          | Hanel et al. (1986); Sori et al. (2017) |
| $d$       | 0.1–1 mm      | Grundy et al. (1999) |
| $k_c$ (pure H$_2$O) | 5 W m$^{-1}$ K$^{-1}$ | Klinger (1980) |
| $k_c$ (H$_2$O with NH$_3$-H$_2$O impurities) | 1–2 W m$^{-1}$ K$^{-1}$ | Lorenz & Shandera (2001) |
| $g$       | 0.27 m s$^2$  | Peale (1999) |
| $\rho$    | 1000 kg m$^{-3}$ | Gammon et al. (1983) |
| $\dot{e}$ | $10^{-17}$–$10^{-14}$ s$^{-1}$ | Giese et al. (2007); Hammond et al. (2013) |

also affect the resulting heat fluxes. However, thermal conductivity values for H$_2$O ice mixed with other materials relevant to the Uranian moons are not currently available, and consequently, we do not consider them in this work. Although large amounts of CO$_2$ are present on Ariel’s surface, this constituent is more likely to be generated by irradiation as opposed to being a native constituent sourced from the lithosphere (Goldsby & Kohlstedt 2001, 2003; Cartwright et al. 2015, 2022).

Nevertheless, when assuming a pure H$_2$O ice lithosphere, our results demonstrate that heat flux estimates in some locations on Ariel may be explained by past orbital resonances. Based on our results, we expect that all seven chasmatas analyzed in this study were present during the heating event that resulted from the initiation of the 4:1 Ariel-Titania MMR, which might have occurred $\sim$3.8 Ga ago (Tittermore & Wisdom 1990). These chasmatas may have formed because of these events and were then subsequently modified to produce the observed flexure. Furthermore, investigation of impact crater distributions across Ariel’s tectonized region in the area between Kachina Chasmata and the Pixie Group found a surface age of only 0.8 Ga ($\sim$0.5/1.8 Ga) (Kirchoff et al. 2022). The age of this younger tectonized region near the south pole may reflect the more recent 5:3 MMR between Ariel and Umbriel that is estimated to have occurred $\sim$1 Ga ago (e.g., Čuk et al. 2020). Therefore, Ariel likely experienced distinct episodes of tectonic resurfacing throughout its geologic history that may reflect past resonances with its neighboring satellites.

4.2. Spatial Variations in Heat Flux

Our results indicate that the region north of the Kachina Group, located near the center of Ariel’s trailing hemisphere, experienced a higher heat flux and lower elastic thickness than the six chasmatas that we analyzed in the Pixie Group. Additionally, the region surrounding Korrigan Chasma, located in the center of the Pixie Group, exhibits a higher heat flux (Peterson et al. 2015) relative to the surrounding Pixie Group chasmatas (Figure 9). These variations in heat fluxes across the surface are mysterious and perhaps are a result of heat concentration in some areas due to interior convection. Additionally, some of Ariel’s impact craters appear to have undergone viscous relaxation based on their shallow depths, including Yangoor and Damovoy, which are located near Ariel’s south pole (Schenk & McKinnon 1988; Bland et al. 2022; Borrelli et al. 2022). These viscously relaxed craters are also consistent with high heat fluxes, but further analysis is needed to estimate the specific heat flux values reflected by these craters.

Perhaps the locations of higher heat fluxes across Ariel’s imaged hemisphere reflect upwelling convection cells in the interior, with higher heat fluxes overlying the center of two cells (in the locations of Kachina and Korrigan) and lower heat fluxes along the margins of these cells. This scenario may be similar to the hypothesized convection cells on Miranda that may have formed the coronae (Hammond & Barr 2014), which are regions with high heat fluxes (Beddingfield et al. 2015a) with evidence for tectonic resurfacing (e.g., Pappalardo et al. 1997; Beddingfield & Cartwright 2020). Convection cell geometries, such as the number, size, and spacing of cells, are affected by various properties of the interior of a planetary body (Schubert et al. 2001; Deschamps et al. 2010; Hammond & Barr 2014). Further investigation into possible interior convection geometries associated with spatial patterns of heat fluxes may provide important insight into the interior properties of Ariel.

4.3. Comparison with Other Icy Bodies

Prior studies that have estimated heat fluxes for other icy satellites, calculated using lithospheric flexure or impact crater relaxation, typically assume pure H$_2$O lithospheres. Consequently, to more appropriately compare Ariel’s heat fluxes to other icy moons, we rely on our estimates that assume a pure H$_2$O lithospheric composition. As shown in Table 3, the estimated heat fluxes for Ariel (6–92 mW m$^{-2}$) are most similar to heat flux estimations for Tethys (Giese et al. 2007; Chen & Nimmo 2008), Dione (Hammond et al. 2013), Rhea (Nimmo et al. 2010; White et al. 2013), Triton (Ruiz 2003; Sori 2021), Pluto (Conrad et al. 2019, 2021), and Charon (Conrad et al. 2021).

Ariel’s heat flux range is somewhat lower than the estimated heat fluxes for Miranda’s Arden Corona (Beddingfield et al. 2015a) and is substantially lower than the heat flux estimations for Enceladus (Bland et al. 2007; Barr 2008; Giese et al. 2008; O’Neill & Nimmo 2010; Bland et al. 2012; Han et al. 2012; Bland et al. 2015; Patthoff et al. 2022). Although our heat flux estimates for Ariel overlap the lower estimates for Europa (Hussmann et al. 2002; Nimmo & Manga 2002; Ruiz 2003; Tobie et al. 2003; Showman & Han 2004; Ruiz 2005) and Ganymede (Nimmo et al. 2002; Nimmo & Pappalardo 2004; Bland et al. 2017), the higher estimates for these two Galilean moons are substantially higher than the estimated heat flux range for Ariel.
Figure 8. Estimated elastic thicknesses across Ariel’s imaged surface (Table 2). The stars are labeled to show the associated chasma: (A) Unnamed Canyon 1 (Figure 4); (B) Kewpie (Figure 4); (C) Brownie (Figure 4); (D) Pixie, northern flank (Figure 4); (E) Pixie, southern flank (Figure 4); (F) Kra (Figure 4); (G) Sylph Chasma, northern flank (Figure 5); (H) Sylph Chasma, southern flank (Figure 5); (I) Kachina Chasmata (Figure 6); (J) Korrigan Chasma, estimated values are from Peterson et al. (2015) (Figure 4). See Figure 2 for the geologic unit and tectonic symbol legends. The nonannotated version of the underlying geologic map is provided in Croft & Soderblom (1991). The results displayed here are also presented in Table 2.

Table 2

| Study Location         | $T_e$ (km) | $F$: Pure H$_2$O (mW m$^{-2}$) | $F$: H$_2$O with H$_2$O-NH$_3$ Impurities (mW m$^{-2}$) | Figure |
|------------------------|------------|-------------------------------|----------------------------------------------------------|--------|
| Unnamed Canyon 1       | 5.7 ± 1.0  | 13–35                         | 3–14                                                     | 3      |
| Kewpie                 | 5.3 ± 0.6  | 14–36                         | 3–14                                                     | 3      |
| Brownie                | 10.3 ± 3.0 | 6–23                          | 1–9                                                      | 3      |
| Pixie (northern flank) | 6.2 ± 1.3  | 10–40                         | 2–16                                                     | 3      |
| Pixie (southern flank) | 9.7 ± 1.3  | 8–20                          | 2–8                                                      | 3      |
| Kra                    | 6.7 ± 0.4  | 12–27                         | 2–11                                                     | 3      |
| Sylph (northern flank) | 6.0 ± 1.4  | 11–37                         | 2–15                                                     | 4      |
| Sylph (southern flank) | 11.4 ± 1.4 | 7–17                          | 1–7                                                      | 4      |
| Kachina                | 4.4 ± 0.7  | 17–46                         | 3–18                                                     | 5      |
| Korrigan$^a$           | 4.1 ± 0.3  | 28–92                         | 5–37                                                     | 3      |

Note. See Figure 8 for the mapped $T_e$ and Figure 9 for the mapped $F$ results.

$^a$ Results for $F$ that assumes a pure H$_2$O ice for Korrigan Chasma are from Peterson et al. (2015). We provide estimates for $F$ in the region of Korrigan Chasma that considers the presence of NH$_3$ hydrates. Our results are based on values for $T_e$ and $T_i$ estimated in Peterson et al. (2015).
4.4. Future Work

New studies that investigate possible explanations for the variations in heat fluxes across Ariel are needed. For example, modeling of possible interior convection geometries associated with the spatial heat flux pattern reported here may provide key insight into the structure and properties of Ariel’s interior. Such interior convection studies could provide constraints on the size of Ariel’s core (Deschamps et al. 2010; Hammond & Barr 2014), the viscosity structure in the interior, the Raleigh number (Schubert et al. 2001; Czechowski & Leliwa-Kopystynski 2005), the distribution of tidal heating (Han & Showman 2010), and the source of heating (Czechowski & Leliwa-Kopystynski 2005). Additionally, possible associations between the spatial heat flux distribution and the distributions expected from various types of stress events that Ariel’s lithosphere may have experienced could be investigated.

New laboratory work that explores how contaminants like NH$_3$-bearing species, carbonates, organics, and phyllosilicates alter the thermal and rheologic properties of icy body interiors are needed to provide a more complete range of expected heat fluxes. Furthermore, subsequent studies are needed to estimate additional heat fluxes for Ariel’s neighboring satellites, including Miranda, Umbriel, Titania, and Oberon, to gain a fuller understanding of the Uranian satellites’ thermal histories and interior properties. Future studies are needed to better understand how NH$_3$ hydrates in Ariel’s lithosphere might change the timescale of radioactive heating. Additionally, investigations into how the rigidity of Ariel’s lithosphere and therefore its $k_2$ Love number are affected by NH$_3$ hydrates are

**Figure 9.** Estimated heat fluxes across Ariel’s imaged surface for pure H$_2$O ice and for H$_2$O ice mixed with NH$_3$ hydrates (Table 2). The stars are labeled to show the associated chasma: (A) Unnamed Canyon 1 (Figure 4); (B) Kewpie (Figure 4); (C) Brownie (Figure 4); (D) Pixie, northern flank (Figure 4); (E) Pixie, southern flank (Figure 4); (F) Kra (Figure 4); (G) Sylph Chasma, northern flank (Figure 5); (H) Sylph Chasma, southern flank (Figure 5); (I) Kachina Chasmata (Figure 6); (J) Korrigan Chasma, estimated values assuming a pure H$_2$O ice lithosphere are from Peterson et al. (2015) (Figure 4). Here we also provide estimated values in this region for a lithosphere that contains NH$_3$ hydrates. These values incorporate the estimated range of values for $T_s$ and $T_e$ discussed in Peterson et al. (2015). See Figure 2 for the geologic unit and tectonic symbol legends. The nonannotated version of the underlying geologic map is provided in Croft & Soderblom (1991). The results displayed here are also presented in Table 2.
needed to better model the amount of energy provided by tidal heating.

As summarized in Cartwright et al. (2021), a Uranus orbiter, making multiple close flybys of Ariel, could provide substantially higher resolution images that would allow us to more fully investigate heat fluxes using finer-scale tectonic features across its surface, including the small medial double ridges within the chasmata, and in regions on the mostly unimaged northern hemisphere of this moon. Additionally, higher-resolution images of Uranus’s outer classical satellites, Umbriel, Titania, and Oberon, are needed to determine whether resurfacing in different regions of their surfaces is associated with geologic activity driven by past orbital resonances and enhanced tidal heating.

An orbiter with a visible/near-infrared mapping spectrometer would allow us to determine whether NH3-bearing species are spatially associated with Ariel’s chasmata, double ridges, and other geologic features and would provide insight into the ages of geologic events and interior compositions (Cartwright et al. 2020, 2021). Furthermore, a magnetometer on an orbiter could search for induced magnetic fields in Ariel, a key diagnostic trait of internal salty oceans (Cochrane et al. 2021; Weiss et al. 2021). Thus, a Uranus orbiter would dramatically improve our understanding of the surface and interior of Ariel, as well as the other Uranian moons, thereby helping us determine whether these moons are, or were, ocean worlds (Beddingfield et al. 2021; Cartwright et al. 2021; Leonard et al. 2021; Bierson & Nimmo 2022; Cohen et al. 2022).

5. Conclusions

We estimate that Ariel’s elastic thickness ranges from 4.1 ± 0.3 km to 11.4 ± 1.4 km across the imaged section of Ariel’s surface. The younger Kachina Group has a relatively low elastic thickness of 4.4 ± 0.7 km compared to most of the chasmata in the older Pixie Group (4.1 ± 0.3 km to 10.3 ± 3.0 km). Conversely, Ariel’s lithosphere exhibits relatively high elastic thickness values in the vicinity of Brownie Chasma (10.3 ± 3.0 km), south of Pixie Chasma (9.7 ± 1.3 km), and south of Sylph Chasma (11.4 ± 1.4 km). The central region of the Pixie Group has a thinner elastic layer, including the region around the Unnamed Canyon (5.7 ± 1.0 km), Kewpie Chasma (5.3 ± 0.6 km), and Korrigan Chasma (4.1 ± 0.3 km; estimated by Peterson et al. 2015).

If Ariel has a pure H2O ice lithosphere, then our heat flux estimates range from 17 to 46 mW m−2 for the Kachina Group and from 6 to 40 mW m−2 for the Pixie Group. Prior work estimated heat fluxes for Korrigan Chasma, ranging from 28 to 92 mW m−2, assuming a pure H2O ice lithosphere (Peterson et al. 2015). Our results for heat flux overlap the lower expected heat fluxes from the 4:1 Ariel-Titania MMR estimated for a lithosphere of pure H2O ice. Alternatively, if NH3 hydrates and other NH3-bearing species are present in Ariel’s lithosphere, then our estimated heat fluxes are substantially lower, ranging from 5 to 18 mW m−2 for the Kachina Group and from 1 to 16 mW m−2 for the Pixie Group.

Our results indicate that accounting for the presence of small amounts of NH3 hydrates in Ariel’s H2O ice lithosphere substantially affects the resulting heat flux estimates. Therefore, the possible presence of this constituent in icy satellite lithospheres should be considered in future work that investigates heat fluxes. Other constituents like carbonates, organics, and phyllosilicates, if present in Ariel’s lithosphere, might also modify the estimated heat fluxes. Future work should consider the possible role of these other lithospheric contaminants, as well as account for radiogenic heating through a lithosphere composed of ice mixed with impurities.

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Appendix

A.1. Digital Elevation Models

To access the accuracy of the DEMs, we used shadow measurement techniques, discussed in Dameron & Burr (2018), to independently estimate the heights of ridges, where shadows were present and measurable in the Voyager 2 ISS images. The shadow measurements were conducted in order to calculate the topographic height, h, of a ridge.
value is given by \( h \frac{s}{\tan(\phi)} \), where \( s \) is the observed shadow length and \( \phi \) is the solar incidence angle. Based on slight differences in ridge heights estimated using these two different techniques, we estimate that the topographic uncertainty associated with each ridge is approximately 20 m per 1 km in elevation. The DEM horizontal resolutions are equivalent to the resolutions of the input Voyager ISS images.

To further access the accuracy of the resulting topography, we measured the depth-diameter \((d-D)\) ratios of impact craters covered by the DEMs and compared our results to \(d-D\) ratios estimated for Ariel independently (Schenk 1991; see Figure A1). The locations of craters analyzed for this work are shown in Figures 2(d), 5(d), and 6(d). We find that the \(d-D\) ratios we measured are consistent with previous estimates, reflecting the accuracy of the DEMs.

### A.2. Flexural Model Uncertainty

Here we show plots that illustrate the flexural profile uncertainties for each study area (Figures A2 and A3).

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**Figure A1.** Depth-diameter \((d-D)\) ratios of impact craters analyzed in the DEMs used for this work (Figure 2) and those analyzed in Schenk (1989). Comparison of these \(d-D\) ratios corroborates the accuracy of the DEMs generated for this work.
**Figure A2.** Combined profile data (gray) with superimposed model flexural profiles that represent the uncertainty minimum (blue) for all chasmata analyzed. The profile line locations for the Unnamed Canyon (Lines 1–5), Kewpie (Lines 6–8), Brownie (Lines 10–13), Pixie (Lines 14–22), and Kra (Lines 23 and 24) are shown in Figure 4. The data for Sylph (Lines 25–45) are shown in Figure 5, and the data for Kachina (Lines 46–65) are shown in Figure 6. See Figure 7 for plots that show the modeled best-fit flexural profiles associated with these data.

**Figure A3.** Combined profile data (gray) with superimposed model flexural profiles that represent the uncertainty maximum (blue) for all chasmata analyzed. The profile line locations for the Unnamed Canyon (Lines 1–5), Kewpie (Lines 6–8), Brownie (Lines 10–13), Pixie (Lines 14–22), and Kra (Lines 23 and 24) are shown in Figure 4. The data for Sylph (Lines 25–45) are shown in Figure 5, and the data for Kachina (Lines 46–65) are shown in Figure 6. See Figure 7 for plots that show the modeled best-fit flexural profiles associated with these data.
### Table A1

Our Results for Heat Flux Estimated Using Various Values for $T_c$, $\dot{\varepsilon}$, $d$, Lithosphere Composition, and $k_c$

| Location          | Minimum $T_c$ (km) | $T_c$: minimum (km); $\dot{\varepsilon}$: $10^{-17}$ s$^{-1}$; $d$: 0.1 mm | $F$ (mW m$^{-2}$); H$_2$O $\left(k_c = 5 \text{ W m}^{-1} \text{ K}^{-1}\right)$ | $F$ (mW m$^{-2}$); NH$_3$-H$_2$O $\left(k_c = 2 \text{ W m}^{-1} \text{ K}^{-1}\right)$ | $F$ (mW m$^{-2}$); NH$_3$-H$_2$O $\left(k_c = 1 \text{ W m}^{-1} \text{ K}^{-1}\right)$ |
|-------------------|-------------------|-------------------------------------------------------------------------------|--------------------------------------------------------------------------|--------------------------------------------------------------------------|--------------------------------------------------------------------------|
| Unnamed Canyon 1  | 4.8               | 18                                                                           | 7                                                                       | 4                                                                        | 4                                                                        |
| Kewpie           | 4.7               | 18                                                                           | 7                                                                       | 4                                                                        | 4                                                                        |
| Brownie          | 7.3               | 12                                                                           | 5                                                                       | 2                                                                        | 2                                                                        |
| Pixie (northern flank) | 4.3             | 20                                                                           | 8                                                                       | 4                                                                        | 4                                                                        |
| Pixie (northern flank) | 8.4             | 10                                                                           | 4                                                                       | 2                                                                        | 2                                                                        |
| Kra              | 6.3               | 13                                                                           | 5                                                                       | 3                                                                        | 3                                                                        |
| Sylph (northern flank) | 4.6             | 18                                                                           | 7                                                                       | 4                                                                        | 4                                                                        |
| Sylph (northern flank) | 10.0            | 8                                                                            | 3                                                                       | 2                                                                        | 2                                                                        |
| Kachina         | 3.7               | 23                                                                           | 9                                                                       | 5                                                                        | 5                                                                        |
| $T_c$: average (km); $\dot{\varepsilon}$: $10^{-17}$ s$^{-1}$; $d$: 0.1 mm |               |                                                                               |                                                                          |                                                                          |                                                                          |
| Location          | Average $T_c$ (km) | $T_c$: average (km); $\dot{\varepsilon}$: $10^{-17}$ s$^{-1}$; $d$: 0.1 mm | $F$ (mW m$^{-2}$); H$_2$O $\left(k_c = 5 \text{ W m}^{-1} \text{ K}^{-1}\right)$ | $F$ (mW m$^{-2}$); NH$_3$-H$_2$O $\left(k_c = 2 \text{ W m}^{-1} \text{ K}^{-1}\right)$ | $F$ (mW m$^{-2}$); NH$_3$-H$_2$O $\left(k_c = 1 \text{ W m}^{-1} \text{ K}^{-1}\right)$ |
| Unnamed Canyon 1  | 5.7               | 15                                                                           | 6                                                                       | 3                                                                        | 3                                                                        |
| Kewpie           | 5.3               | 16                                                                           | 6                                                                       | 3                                                                        | 3                                                                        |
| Brownie          | 10.3              | 8                                                                            | 3                                                                       | 2                                                                        | 2                                                                        |
| Pixie (northern flank) | 6.2             | 14                                                                           | 5                                                                       | 3                                                                        | 3                                                                        |
| Kra              | 6.7               | 13                                                                           | 5                                                                       | 3                                                                        | 3                                                                        |
| Sylph (northern flank) | 6.0             | 14                                                                           | 6                                                                       | 3                                                                        | 3                                                                        |
| Kachina         | 4.4               | 19                                                                           | 8                                                                       | 4                                                                        | 4                                                                        |
| $T_c$: maximum (km); $\dot{\varepsilon}$: $10^{-17}$ s$^{-1}$; $d$: 0.1 mm |               |                                                                               |                                                                          |                                                                          |                                                                          |
| Location          | Maximum $T_c$ (km) | $T_c$: maximum (km); $\dot{\varepsilon}$: $10^{-17}$ s$^{-1}$; $d$: 0.1 mm | $F$ (mW m$^{-2}$); H$_2$O $\left(k_c = 5 \text{ W m}^{-1} \text{ K}^{-1}\right)$ | $F$ (mW m$^{-2}$); NH$_3$-H$_2$O $\left(k_c = 2 \text{ W m}^{-1} \text{ K}^{-1}\right)$ | $F$ (mW m$^{-2}$); NH$_3$-H$_2$O $\left(k_c = 1 \text{ W m}^{-1} \text{ K}^{-1}\right)$ |
| Unnamed Canyon 1  | 6.7               | 13                                                                           | 5                                                                       | 3                                                                        | 3                                                                        |
| Kewpie           | 6.0               | 14                                                                           | 6                                                                       | 3                                                                        | 3                                                                        |
| Brownie          | 13.4              | 6                                                                            | 3                                                                       | 1                                                                        | 1                                                                        |
| Pixie (northern flank) | 8.1             | 10                                                                           | 4                                                                       | 2                                                                        | 2                                                                        |
| Kra              | 7.1               | 12                                                                           | 5                                                                       | 2                                                                        | 2                                                                        |
| Sylph (northern flank) | 7.4             | 11                                                                           | 5                                                                       | 2                                                                        | 2                                                                        |
| Kachina         | 5.1               | 17                                                                           | 7                                                                       | 3                                                                        | 3                                                                        |
| $T_c$: minimum (km); $\dot{\varepsilon}$: $10^{-18}$ s$^{-1}$; $d$: 0.1 mm |               |                                                                               |                                                                          |                                                                          |                                                                          |
| Location          | Average $T_c$ (km) | $T_c$: average (km); $\dot{\varepsilon}$: $10^{-18}$ s$^{-1}$; $d$: 1 mm | $F$ (mW m$^{-2}$); H$_2$O $\left(k_c = 5 \text{ W m}^{-1} \text{ K}^{-1}\right)$ | $F$ (mW m$^{-2}$); NH$_3$-H$_2$O $\left(k_c = 2 \text{ W m}^{-1} \text{ K}^{-1}\right)$ | $F$ (mW m$^{-2}$); NH$_3$-H$_2$O $\left(k_c = 1 \text{ W m}^{-1} \text{ K}^{-1}\right)$ |
| Unnamed Canyon 1  | 5.7               | 19                                                                           | 8                                                                       | 4                                                                        | 4                                                                        |
| Kewpie           | 5.3               | 20                                                                           | 8                                                                       | 4                                                                        | 4                                                                        |
| Brownie          | 10.3              | 11                                                                           | 4                                                                       | 2                                                                        | 2                                                                        |
| Pixie (northern flank) | 6.2             | 17                                                                           | 7                                                                       | 3                                                                        | 3                                                                        |
| Kra              | 6.7               | 16                                                                           | 6                                                                       | 3                                                                        | 3                                                                        |
| Sylph (northern flank) | 6.0             | 18                                                                           | 7                                                                       | 4                                                                        | 4                                                                        |
| Kachina         | 4.4               | 25                                                                           | 10                                                                      | 5                                                                        | 5                                                                        |
| $T_c$: average (km); $\dot{\varepsilon}$: $10^{-18}$ s$^{-1}$; $d$: 1 mm |               |                                                                               |                                                                          |                                                                          |                                                                          |
| Location          | Maximum $T_c$ (km) | $T_c$: average (km); $\dot{\varepsilon}$: $10^{-18}$ s$^{-1}$; $d$: 1 mm | $F$ (mW m$^{-2}$); H$_2$O $\left(k_c = 5 \text{ W m}^{-1} \text{ K}^{-1}\right)$ | $F$ (mW m$^{-2}$); NH$_3$-H$_2$O $\left(k_c = 2 \text{ W m}^{-1} \text{ K}^{-1}\right)$ | $F$ (mW m$^{-2}$); NH$_3$-H$_2$O $\left(k_c = 1 \text{ W m}^{-1} \text{ K}^{-1}\right)$ |
| Unnamed Canyon 1  | 6.7               | 16                                                                           | 6                                                                       | 3                                                                        | 3                                                                        |
| Kewpie           | 6.0               | 18                                                                           | 7                                                                       | 4                                                                        | 4                                                                        |
| Brownie          | 13.4              | 8                                                                            | 3                                                                       | 2                                                                        | 2                                                                        |
| Pixie (northern flank) | 8.1             | 13                                                                           | 5                                                                       | 3                                                                        | 3                                                                        |
| Kra              | 7.1               | 15                                                                           | 6                                                                       | 3                                                                        | 3                                                                        |
| Sylph (northern flank) | 7.4             | 15                                                                           | 6                                                                       | 3                                                                        | 3                                                                        |
| Kachina         | 5.1               | 21                                                                           | 9                                                                       | 4                                                                        | 4                                                                        |
Table A1 (Continued)

| Location                  | Minimum $T_e$ (km) | $F$ (mW m$^{-2}$): H$_2$O ($k_e = 5$ W m$^{-1}$ K$^{-1}$) | $F$ (mW m$^{-2}$): NH$_3$-H$_2$O ($k_e = 2$ W m$^{-1}$ K$^{-1}$) | $F$ (mW m$^{-2}$): NH$_3$-H$_2$O ($k_e = 1$ W m$^{-1}$ K$^{-1}$) |
|---------------------------|--------------------|----------------------------------------------------------|----------------------------------------------------------|----------------------------------------------------------|
| Unnamed Canyon 1          | 4.8                | 21                                                       | 8                                                        | 4                                                        |
| Kewpie                    | 4.7                | 22                                                       | 9                                                        | 4                                                        |
| Brownie                   | 7.3                | 14                                                       | 6                                                        | 3                                                        |
| Pixie (northern flank)    | 4.3                | 24                                                       | 5                                                        | 2                                                        |
| Pixie (southern flank)    | 8.4                | 12                                                       | 5                                                        | 2                                                        |
| Kra                       | 6.3                | 16                                                       | 6                                                        | 3                                                        |
| Sylph (northern flank)    | 4.6                | 22                                                       | 9                                                        | 4                                                        |
| Sylph (southern flank)    | 10.0               | 10                                                       | 4                                                        | 2                                                        |
| Kachina                   | 3.7                | 27                                                       | 11                                                       | 5                                                        |
| $T_e$: average (km); $\dot{\epsilon}$: 10$^{-16}$ s$^{-1}$; $d$: 0.1 mm |           |                                                          |                                                          |                                                          |
| Location                  | Average $T_e$ (km) | $F$ (mW m$^{-2}$): H$_2$O ($k_e = 5$ W m$^{-1}$ K$^{-1}$) | $F$ (mW m$^{-2}$): NH$_3$-H$_2$O ($k_e = 2$ W m$^{-1}$ K$^{-1}$) | $F$ (mW m$^{-2}$): NH$_3$-H$_2$O ($k_e = 1$ W m$^{-1}$ K$^{-1}$) |
| Unnamed Canyon 1          | 5.7                | 18                                                       | 7                                                        | 4                                                        |
| Kewpie                    | 5.3                | 19                                                       | 8                                                        | 4                                                        |
| Brownie                   | 10.3               | 10                                                       | 4                                                        | 2                                                        |
| Pixie (northern flank)    | 6.2                | 16                                                       | 7                                                        | 3                                                        |
| Pixie (southern flank)    | 9.7                | 10                                                       | 4                                                        | 2                                                        |
| Kra                       | 6.7                | 15                                                       | 6                                                        | 3                                                        |
| Sylph (northern flank)    | 6.0                | 17                                                       | 7                                                        | 3                                                        |
| Sylph (southern flank)    | 11.4               | 9                                                        | 4                                                        | 2                                                        |
| Kachina                   | 4.4                | 23                                                       | 9                                                        | 5                                                        |
| $T_e$: maximum (km); $\dot{\epsilon}$: 10$^{-16}$ s$^{-1}$; $d$: 0.1 mm |           |                                                          |                                                          |                                                          |
| Location                  | Minimum $T_e$ (km) | $F$ (mW m$^{-2}$): H$_2$O ($k_e = 5$ W m$^{-1}$ K$^{-1}$) | $F$ (mW m$^{-2}$): NH$_3$-H$_2$O ($k_e = 2$ W m$^{-1}$ K$^{-1}$) | $F$ (mW m$^{-2}$): NH$_3$-H$_2$O ($k_e = 1$ W m$^{-1}$ K$^{-1}$) |
| Unnamed Canyon 1          | 6.7                | 15                                                       | 6                                                        | 3                                                        |
| Kewpie                    | 6.0                | 17                                                       | 7                                                        | 3                                                        |
| Brownie                   | 13.4               | 8                                                        | 3                                                        | 2                                                        |
| Pixie (northern flank)    | 8.1                | 13                                                       | 5                                                        | 3                                                        |
| Pixie (southern flank)    | 11.0               | 9                                                        | 4                                                        | 2                                                        |
| Kra                       | 7.1                | 14                                                       | 6                                                        | 3                                                        |
| Sylph (northern flank)    | 7.4                | 14                                                       | 5                                                        | 3                                                        |
| Sylph (southern flank)    | 12.8               | 8                                                        | 3                                                        | 2                                                        |
| Kachina                   | 5.1                | 20                                                       | 8                                                        | 4                                                        |
| $T_e$: minimum (km); $\dot{\epsilon}$: 10$^{-16}$ s$^{-1}$; $d$: 1 mm |           |                                                          |                                                          |                                                          |
| Location                  | Minimum $T_e$ (km) | $F$ (mW m$^{-2}$): H$_2$O ($k_e = 5$ W m$^{-1}$ K$^{-1}$) | $F$ (mW m$^{-2}$): NH$_3$-H$_2$O ($k_e = 2$ W m$^{-1}$ K$^{-1}$) | $F$ (mW m$^{-2}$): NH$_3$-H$_2$O ($k_e = 1$ W m$^{-1}$ K$^{-1}$) |
| Unnamed Canyon 1          | 4.8                | 27                                                       | 11                                                       | 5                                                        |
| Kewpie                    | 4.7                | 27                                                       | 11                                                       | 5                                                        |
| Brownie                   | 7.3                | 17                                                       | 7                                                        | 3                                                        |
| Pixie (northern flank)    | 4.3                | 30                                                       | 12                                                       | 6                                                        |
| Pixie (southern flank)    | 8.4                | 15                                                       | 6                                                        | 3                                                        |
| Kra                       | 6.3                | 20                                                       | 8                                                        | 4                                                        |
| Sylph (northern flank)    | 4.6                | 28                                                       | 11                                                       | 6                                                        |
| Sylph (southern flank)    | 10.0               | 13                                                       | 5                                                        | 3                                                        |
| Kachina                   | 3.7                | 34                                                       | 14                                                       | 7                                                        |
| $T_e$: average (km); $\dot{\epsilon}$: 10$^{-16}$ s$^{-1}$; $d$: 1 mm |           |                                                          |                                                          |                                                          |
| Location                  | Average $T_e$ (km) | $F$ (mW m$^{-2}$): H$_2$O ($k_e = 5$ W m$^{-1}$ K$^{-1}$) | $F$ (mW m$^{-2}$): NH$_3$-H$_2$O ($k_e = 2$ W m$^{-1}$ K$^{-1}$) | $F$ (mW m$^{-2}$): NH$_3$-H$_2$O ($k_e = 1$ W m$^{-1}$ K$^{-1}$) |
| Unnamed Canyon 1          | 5.7                | 22                                                       | 9                                                        | 4                                                        |
| $T_e$: average (km); $\dot{\epsilon}$: 10$^{-16}$ s$^{-1}$; $d$: 1 mm |           |                                                          |                                                          |                                                          |
| Location                  | Maximum $T_e$ (km) | $F$ (mW m$^{-2}$): H$_2$O ($k_e = 5$ W m$^{-1}$ K$^{-1}$) | $F$ (mW m$^{-2}$): NH$_3$-H$_2$O ($k_e = 2$ W m$^{-1}$ K$^{-1}$) | $F$ (mW m$^{-2}$): NH$_3$-H$_2$O ($k_e = 1$ W m$^{-1}$ K$^{-1}$) |
| Unnamed Canyon 1          | 6.7                | 19                                                       | 8                                                        | 4                                                        |
| Kewpie                    | 6.0                | 21                                                       | 8                                                        | 4                                                        |
| Brownie                   | 13.4               | 10                                                       | 4                                                        | 2                                                        |
| Pixie (northern flank)    | 8.1                | 16                                                       | 6                                                        | 3                                                        |
| Pixie (southern flank)    | 11.0               | 12                                                       | 5                                                        | 2                                                        |
| Kra                       | 7.1                | 18                                                       | 7                                                        | 4                                                        |
| Sylph (northern flank)    | 7.4                | 17                                                       | 7                                                        | 3                                                        |
| Sylph (southern flank)    | 12.8               | 10                                                       | 4                                                        | 2                                                        |
| Kachina                   | 5.1                | 25                                                       | 10                                                       | 5                                                        |
| Location                  | Minimum $T_e$ (km) | $F$ (mW m$^{-2}$): H$_2$O ($k_e = 5$ W m$^{-1}$ K$^{-1}$) | $F$ (mW m$^{-2}$): NH$_3$-H$_2$O ($k_e = 2$ W m$^{-1}$ K$^{-1}$) | $F$ (mW m$^{-2}$): NH$_3$-H$_2$O ($k_e = 1$ W m$^{-1}$ K$^{-1}$) |
|--------------------------|-------------------|------------------------------------------------------------|-------------------------------------------------------------|-------------------------------------------------------------|
| Unnamed Canyon 1         | 4.8               | 25                                                         | 10                                                          | 5                                                           |
| Kewpie                   | 4.7               | 25                                                         | 10                                                          | 5                                                           |
| Brownie                  | 7.3               | 16                                                         | 7                                                           | 3                                                           |
| Pixie (northern flank)   | 4.3               | 28                                                         | 11                                                          | 6                                                           |
| Pixie (southern flank)   | 8.4               | 14                                                         | 6                                                           | 3                                                           |
| Kra                      | 6.3               | 19                                                         | 8                                                           | 4                                                           |
| Sylph (northern flank)   | 4.6               | 26                                                         | 10                                                          | 5                                                           |
| Sylph (southern flank)   | 10.0              | 12                                                         | 5                                                           | 2                                                           |
| Kachina                  | 3.7               | 32                                                         | 13                                                          | 6                                                           |

$T_e$: average (km); $\dot{T}_e$: $10^{-15}$ s$^{-1}$; $d$: 0.1 mm

| Location                  | Average $T_e$ (km) | $F$ (mW m$^{-2}$): H$_2$O ($k_e = 5$ W m$^{-1}$ K$^{-1}$) | $F$ (mW m$^{-2}$): NH$_3$-H$_2$O ($k_e = 2$ W m$^{-1}$ K$^{-1}$) | $F$ (mW m$^{-2}$): NH$_3$-H$_2$O ($k_e = 1$ W m$^{-1}$ K$^{-1}$) |
|--------------------------|-------------------|------------------------------------------------------------|-------------------------------------------------------------|-------------------------------------------------------------|
| Unnamed Canyon 1         | 5.7               | 21                                                         | 8                                                           | 4                                                           |
| Kewpie                   | 5.3               | 23                                                         | 9                                                           | 5                                                           |
| Brownie                  | 10.3              | 12                                                         | 5                                                           | 2                                                           |
| Pixie (northern flank)   | 6.2               | 19                                                         | 8                                                           | 4                                                           |
| Pixie (southern flank)   | 9.7               | 12                                                         | 5                                                           | 2                                                           |
| Kra                      | 6.7               | 18                                                         | 7                                                           | 4                                                           |
| Sylph (northern flank)   | 6.0               | 20                                                         | 8                                                           | 4                                                           |
| Sylph (southern flank)   | 11.4              | 11                                                         | 4                                                           | 2                                                           |
| Kachina                  | 4.4               | 27                                                         | 11                                                          | 5                                                           |

$T_e$: maximum (km); $\dot{T}_e$: $10^{-15}$ s$^{-1}$; $d$: 0.1 mm

| Location                  | Minimum $T_e$ (km) | $F$ (mW m$^{-2}$): H$_2$O ($k_e = 5$ W m$^{-1}$ K$^{-1}$) | $F$ (mW m$^{-2}$): NH$_3$-H$_2$O ($k_e = 2$ W m$^{-1}$ K$^{-1}$) | $F$ (mW m$^{-2}$): NH$_3$-H$_2$O ($k_e = 1$ W m$^{-1}$ K$^{-1}$) |
|--------------------------|-------------------|------------------------------------------------------------|-------------------------------------------------------------|-------------------------------------------------------------|
| Unnamed Canyon 1         | 4.8               | 31                                                         | 12                                                          | 6                                                           |
| Kewpie                   | 4.7               | 31                                                         | 13                                                          | 6                                                           |
| Brownie                  | 7.3               | 20                                                         | 8                                                           | 4                                                           |
| Pixie (northern flank)   | 4.3               | 34                                                         | 14                                                          | 7                                                           |
| Pixie (southern flank)   | 8.4               | 18                                                         | 7                                                           | 4                                                           |

$T_e$: average (km); $\dot{T}_e$: $10^{-15}$ s$^{-1}$; $d$: 1 mm

| Location                  | Maximum $T_e$ (km) | $F$ (mW m$^{-2}$): H$_2$O ($k_e = 5$ W m$^{-1}$ K$^{-1}$) | $F$ (mW m$^{-2}$): NH$_3$-H$_2$O ($k_e = 2$ W m$^{-1}$ K$^{-1}$) | $F$ (mW m$^{-2}$): NH$_3$-H$_2$O ($k_e = 1$ W m$^{-1}$ K$^{-1}$) |
|--------------------------|-------------------|------------------------------------------------------------|-------------------------------------------------------------|-------------------------------------------------------------|
| Unnamed Canyon 1         | 6.7               | 18                                                         | 7                                                           | 4                                                           |
| Kewpie                   | 6.0               | 20                                                         | 8                                                           | 4                                                           |
| Brownie                  | 13.4              | 9                                                          | 4                                                           | 2                                                           |
| Pixie (northern flank)   | 8.1               | 15                                                         | 6                                                           | 3                                                           |
| Pixie (southern flank)   | 11.0              | 11                                                         | 4                                                           | 2                                                           |
| Kra                      | 7.1               | 17                                                         | 7                                                           | 3                                                           |
| Sylph (northern flank)   | 7.4               | 16                                                         | 6                                                           | 3                                                           |
| Sylph (southern flank)   | 12.8              | 9                                                          | 4                                                           | 2                                                           |
| Kachina                  | 5.1               | 23                                                         | 9                                                           | 5                                                           |

$T_e$: minimum (km); $\dot{T}_e$: $10^{-15}$ s$^{-1}$; $d$: 1 mm

| Location                  | Average $T_e$ (km) | $F$ (mW m$^{-2}$): H$_2$O ($k_e = 5$ W m$^{-1}$ K$^{-1}$) | $F$ (mW m$^{-2}$): NH$_3$-H$_2$O ($k_e = 2$ W m$^{-1}$ K$^{-1}$) | $F$ (mW m$^{-2}$): NH$_3$-H$_2$O ($k_e = 1$ W m$^{-1}$ K$^{-1}$) |
|--------------------------|-------------------|------------------------------------------------------------|-------------------------------------------------------------|-------------------------------------------------------------|
| Unnamed Canyon 1         | 5.7               | 26                                                         | 10                                                          | 5                                                           |
| Kewpie                   | 5.3               | 28                                                         | 11                                                          | 6                                                           |
| Brownie                  | 10.3              | 14                                                         | 6                                                           | 3                                                           |
| Pixie (northern flank)   | 6.2               | 24                                                         | 10                                                          | 5                                                           |
| Pixie (southern flank)   | 9.7               | 15                                                         | 6                                                           | 3                                                           |
| Kra                      | 6.7               | 22                                                         | 9                                                           | 4                                                           |
| Sylph (northern flank)   | 6.0               | 25                                                         | 10                                                          | 5                                                           |
| Sylph (southern flank)   | 11.4              | 13                                                         | 5                                                           | 3                                                           |
| Kachina                  | 4.4               | 34                                                         | 13                                                          | 7                                                           |

$T_e$: average (km); $\dot{T}_e$: $10^{-15}$ s$^{-1}$; $d$: 1 mm

| Location                  | Maximum $T_e$ (km) | $F$ (mW m$^{-2}$): H$_2$O ($k_e = 5$ W m$^{-1}$ K$^{-1}$) | $F$ (mW m$^{-2}$): NH$_3$-H$_2$O ($k_e = 2$ W m$^{-1}$ K$^{-1}$) | $F$ (mW m$^{-2}$): NH$_3$-H$_2$O ($k_e = 1$ W m$^{-1}$ K$^{-1}$) |
|--------------------------|-------------------|------------------------------------------------------------|-------------------------------------------------------------|-------------------------------------------------------------|
| Unnamed Canyon 1         | 6.7               | 22                                                         | 9                                                           | 4                                                           |
| Kewpie                   | 6.0               | 25                                                         | 10                                                          | 5                                                           |
| Brownie                  | 13.4              | 11                                                         | 4                                                           | 2                                                           |
| Pixie (northern flank)   | 8.1               | 18                                                         | 7                                                           | 4                                                           |
| Pixie (southern flank)   | 11.0              | 13                                                         | 5                                                           | 3                                                           |
| Kra                      | 7.1               | 21                                                         | 8                                                           | 4                                                           |
| Sylph (northern flank)   | 7.4               | 20                                                         | 8                                                           | 4                                                           |
| Sylph (southern flank)   | 12.8              | 12                                                         | 5                                                           | 2                                                           |
| Kachina                  | 5.1               | 29                                                         | 12                                                          | 6                                                           |

$T_e$: minimum (km); $\dot{T}_e$: $10^{-14}$ s$^{-1}$; $d$: 0.1 mm

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Table A1 (Continued)
| Location                  | Minimum $T_e$ (km) | $F$ (mW m$^{-2}$): $H_2O$  
$(k_e = 5 \text{ W m}^{-1} \text{ K}^{-1})$ | $F$ (mW m$^{-2}$): $NH_3$-$H_2O$  
$(k_e = 2 \text{ W m}^{-1} \text{ K}^{-1})$ | $F$ (mW m$^{-2}$): $NH_3$-$H_2O$  
$(k_e = 1 \text{ W m}^{-1} \text{ K}^{-1})$ |
|--------------------------|-------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| Unnamed Canyon 1         | 4.8               | 29                                              | 12                                              | 6                                               |
| Kewpie                   | 4.7               | 30                                              | 12                                              | 6                                               |
| Brownie                  | 7.3               | 19                                              | 8                                               | 4                                               |
| Pixie (northern flank)   | 4.3               | 32                                              | 13                                              | 6                                               |
| Pixie (southern flank)   | 8.4               | 17                                              | 7                                               | 3                                               |
| Kra                      | 6.3               | 22                                              | 9                                               | 4                                               |
| Sylvph (northern flank)  | 4.6               | 30                                              | 12                                              | 6                                               |
| Sylvph (southern flank)  | 10.0              | 14                                              | 6                                               | 3                                               |
| Kachina                  | 3.7               | 38                                              | 15                                              | 8                                               |
| $T_e$: average (km); $i$: $10^{-14}$ s$^{-1}$; $d$: 0.1 mm |
| Location                  | Average $T_e$ (km) | $F$ (mW m$^{-2}$): $H_2O$  
$(k_e = 5 \text{ W m}^{-1} \text{ K}^{-1})$ | $F$ (mW m$^{-2}$): $NH_3$-$H_2O$  
$(k_e = 2 \text{ W m}^{-1} \text{ K}^{-1})$ | $F$ (mW m$^{-2}$): $NH_3$-$H_2O$  
$(k_e = 1 \text{ W m}^{-1} \text{ K}^{-1})$ |
| Unnamed Canyon 1         | 5.7               | 24                                              | 10                                              | 5                                               |
| Kewpie                   | 5.3               | 26                                              | 11                                              | 5                                               |
| Brownie                  | 10.3              | 14                                              | 5                                               | 3                                               |
| Pixie (northern flank)   | 6.2               | 23                                              | 9                                               | 5                                               |
| Pixie (southern flank)   | 9.7               | 14                                              | 6                                               | 3                                               |
| Kra                      | 6.7               | 21                                              | 8                                               | 4                                               |
| Sylvph (northern flank)  | 6.0               | 23                                              | 9                                               | 5                                               |
| Sylvph (southern flank)  | 11.4              | 12                                              | 5                                               | 2                                               |
| Kachina                  | 4.4               | 32                                              | 13                                              | 6                                               |
| $T_e$: maximum (km); $i$: $10^{-14}$ s$^{-1}$; $d$: 0.1 mm |
| Location                  | Minimum $T_e$ (km) | $F$ (mW m$^{-2}$): $H_2O$  
$(k_e = 5 \text{ W m}^{-1} \text{ K}^{-1})$ | $F$ (mW m$^{-2}$): $NH_3$-$H_2O$  
$(k_e = 2 \text{ W m}^{-1} \text{ K}^{-1})$ | $F$ (mW m$^{-2}$): $NH_3$-$H_2O$  
$(k_e = 1 \text{ W m}^{-1} \text{ K}^{-1})$ |
| Unnamed Canyon 1         | 6.7               | 21                                              | 8                                               | 4                                               |
| Kewpie                   | 6.0               | 23                                              | 9                                               | 5                                               |
| Brownie                  | 13.4              | 10                                              | 4                                               | 2                                               |
| Pixie (northern flank)   | 8.1               | 17                                              | 7                                               | 3                                               |
| Pixie (southern flank)   | 11.0              | 13                                              | 5                                               | 3                                               |
| Kra                      | 7.1               | 20                                              | 8                                               | 4                                               |
| Sylvph (northern flank)  | 7.4               | 19                                              | 8                                               | 4                                               |
| Sylvph (southern flank)  | 12.8              | 11                                              | 4                                               | 2                                               |
| Kachina                  | 5.1               | 27                                              | 11                                              | 5                                               |
| $T_e$: minimum (km); $i$: $10^{-14}$ s$^{-1}$; $d$: 1 mm |
| Location                  | Minimum $T_e$ (km) | $F$ (mW m$^{-2}$): $H_2O$  
$(k_e = 5 \text{ W m}^{-1} \text{ K}^{-1})$ | $F$ (mW m$^{-2}$): $NH_3$-$H_2O$  
$(k_e = 2 \text{ W m}^{-1} \text{ K}^{-1})$ | $F$ (mW m$^{-2}$): $NH_3$-$H_2O$  
$(k_e = 1 \text{ W m}^{-1} \text{ K}^{-1})$ |
| Unnamed Canyon 1         | 4.8               | 35                                              | 14                                              | 7                                               |
| Kewpie                   | 4.7               | 36                                              | 14                                              | 7                                               |
| Brownie                  | 7.3               | 23                                              | 9                                               | 5                                               |
| Pixie (northern flank)   | 4.3               | 40                                              | 8                                               | 4                                               |
| Pixie (southern flank)   | 8.4               | 20                                              | 8                                               | 4                                               |
| Kra                      | 6.3               | 27                                              | 11                                              | 5                                               |
| Sylvph (northern flank)  | 4.6               | 37                                              | 15                                              | 7                                               |
| Sylvph (southern flank)  | 10.0              | 17                                              | 7                                               | 3                                               |
| Kachina                  | 3.7               | 46                                              | 18                                              | 9                                               |
| $T_e$: average (km); $i$: $10^{-14}$ s$^{-1}$; $d$: 1 mm |
| Location                  | Average $T_e$ (km) | $F$ (mW m$^{-2}$): $H_2O$  
$(k_e = 5 \text{ W m}^{-1} \text{ K}^{-1})$ | $F$ (mW m$^{-2}$): $NH_3$-$H_2O$  
$(k_e = 2 \text{ W m}^{-1} \text{ K}^{-1})$ | $F$ (mW m$^{-2}$): $NH_3$-$H_2O$  
$(k_e = 1 \text{ W m}^{-1} \text{ K}^{-1})$ |
| Unnamed Canyon 1         | 5.7               | 30                                              | 12                                              | 6                                               |
| Kewpie                   | 5.3               | 32                                              | 13                                              | 6                                               |
| Brownie                  | 10.3              | 17                                              | 7                                               | 3                                               |
| Pixie (northern flank)   | 6.2               | 27                                              | 11                                              | 5                                               |
| Pixie (southern flank)   | 9.7               | 18                                              | 7                                               | 3                                               |
| Kra                      | 6.7               | 25                                              | 10                                              | 5                                               |
| Sylvph (northern flank)  | 6.0               | 28                                              | 11                                              | 6                                               |
| Sylvph (southern flank)  | 11.4              | 15                                              | 6                                               | 3                                               |
| Kachina                  | 4.4               | 39                                              | 15                                              | 8                                               |
| $T_e$: maximum (km); $i$: $10^{-14}$ s$^{-1}$; $d$: 1 mm |
References

A.3. Additional Heat Flux Results

Here we show our heat flux results for each chasma and for all variables used (Table A1).

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Beddingfield et al.

Geissler, P., Greenberg, R., Hoppa, G., et al. 1998, Nature, 391, 368

Giese, B., Wagner, R., Hussmann, H., et al. 2008, GeoRL, 35, L24204

Giese, B., Wagner, R., Neukum, G., Helfenstein, P., & Thomas, P. C. 2007, GeoRL, 34, L12103

Goldsbey, D., & Kohlstedt, D. L. 2001, JGR, 106, 11017

Grundy, W., Buie, M., Stansberry, J., Spencer, J., & Schmidt, B. 1999, Icar, 142, 536

Grundy, W., Young, L., Spencer, J., et al. 2006, Icar, 184, 543

Grundy, W., Young, L., & Young, E. 2003, Icar, 162, 222

Hammond, N., Phillips, C., Nimm, F., & Kattenhorn, S. 2013, Icar, 223, 418

Hammond, N. P., & Barr, A. C. 2014, Geo, 42, 931

Han, L., & Showman, A. P. 2010, Icar, 207, 834

Han, L., Tobie, G., & Showman, A. P. 2012, Icar, 218, 320

Hanel, R., Conrath, B., Flasar, F., et al. 1986, Sci, 233, 70

Hussmann, H., Choblet, G., Lainey, V., et al. 2010, SSRv, 153, 317

Hussmann, H., Spohn, T., & Wieczerkowski, K. 2002, Icar, 156, 143

Jankowski, D. G., & Squires, S. W. 1988, Sci, 241, 1322

Kargel, J. 1988, LPS, 19, 581

Kirchoff, M. R., Dones, L., Singer, K., & Schenk, P. 2022, PSJ, 3, 42

Klinger, J. 1980, Sci, 209, 271

Leonard, E., Pappalardo, R., & Yin, A. 2018, Icar, 312, 100

Leonard, E. J., Elder, C., Nordheim, T. A., et al. 2021, PSJ, 2, 174

Lewis, J. S. 1972, EPSL, 15, 286

Lorenz, R. D., & Shandera, S. E. 2001, GeoRL, 28, 215

Manckelov, N. 2009, JGR, 21, 161

McNutt, M. K. 1984, JGR, 89, 11180

Moore, M. H., Ferrante, R., Hudson, R., & Stone, J. 2007, Icar, 190, 260

Moratto, Z. M., Broxton, M. J., Beyer, R. A., Lundy, M., & Husmann, K. 2010, LPI, 41, 2364

Nimmo, F., Bills, B., Thomas, P., & Asmar, S. 2010, JGRE, 115, E10008

Nimmo, F., & Manga, M. 2002, GeoRL, 29, 2109

Nimmo, F., & Pappalardo, R. 2004, GeoRL, 31, L19701

Nimmo, F., & Pappalardo, R. 2016, JGRE, 121, 1578

Nimmo, F., Pappalardo, R., & Giese, B. 2003, Icar, 166, 21

Nimmo, F., Pappalardo, R. T., & Giese, B. 2002, GeoRL, 29, 1158

O’Neill, C., & Nimmo, F. 2010, NatGe, 3, 88

Pappalardo, R. T., Belton, M. J., Breneman, H., et al. 1999, IGR, 104, 24015

Pappalardo, R. T., Reynolds, S. J., & Greeley, R. 1997, JGR, 102, 13369

Patthoff, D., Pappalardo, R., Golombek, M., et al. 2022, Icar, 375, 114815

Peale, S. 1999, ARA&A, 37, 533

Peterson, G., Nimmo, F., & Schenk, P. 2015, Icar, 250, 116

Plescia, J. 1987, Natur, 327, 201

Prinn, R., & Fegley, B., Jr 1989, Origin and Evolution of Planetary and Satellite Atmospheres (Tucson, AZ: Univ. Arizona Press), 78

Prowecker, L. M., Nimmo, F., & Pappalardo, R. T. 2005, GeoRL, 32, L14202

Rui, J. 2003, Icar, 166, 436

Rui, J. 2005, Icar, 177, 438

Schenk, P., & McKinley, W. 1988, BAAS, 20, 881

Schenk, P. M. 1989, JGR, 94, 3813

Schenk, P. M. 1991, JGR, 96, 1887

Schenk, P. M., & Moore, J. M. 2020, RSPTA, 378, 20200102

Schubert, G., Turcotte, D. L., & Olson, P. 2001, Mantle Convection in the Earth and Planets (Cambridge: Cambridge Univ. Press)

Showman, A. P., & Han, L. 2004, JGRE, 109, E01010

Smith, B. A., Soderblom, L., Beebe, R., et al. 1986, Sci, 233, 43

Sori, M. M. 2021, GeoRL, 48, e09518

Sori, M. M., Bapts, J., Bramson, A. M., Byrne, S., & Landis, M. E. 2017, Icar, 290, 1

Thomas, P. 1988, Icar, 73, 427

Tittinemore, W. C., & Wisdom, J. 1990, Icar, 85, 394

Tobie, G., Choblet, G., & Cotin, C. 2003, JGRE, 108, 5124

Weiss, B. P., Biersteker, J. B., Collici, V., et al. 2021, GeoRL, 48, e09758

White, O. L., Schenk, P. M., & Dombard, A. J. 2013, Icar, 223, 699