ELEVATED HEAT FLUX ON URANUS' MOON ARIEL INFERRED FROM ITS LARGEST OBSERVED IMPACT CRATER. M. T. Bland[1], T. A. Nordheim[2], D. A. Patthoff[3], and S. D. Vance[2], [1]U. S. Geological Survey, Astrogeology Science Center, Flagstaff AZ, USA (mbland@usgs.gov), [2]Jet Propulsion Laboratory, Pasadena CA, USA, [3]Planetary Science Institute, Tucson AZ USA.

Introduction: Uranus' mid-sized moon, Ariel, (radius of 578.9 km) exhibits a complex geologic history that includes the formation of massive graben and possible cryovolcanic resurfacing [1]. This contrasts with its neighbor Umbriel, which despite its nearly identical size has a dark, ancient surface dominated by impact craters [1]. The two moons must have experienced different thermal and orbital histories that produced different stress, energy dissipation, and/or interior evolution. Here we use observations of Ariel's largest crater, Yangoor, to better constrain the thermal conditions in Ariel's past.

Ariel's Impact Craters – Evidence for Viscous Relaxation: Ariel's cratered terrains have crater densities less than those on Titania, Umbriel, and Oberon, with a particular dearth of large craters [1,2]. Although the average depth-diameter (d/D) trend of fresh simple craters on Ariel is similar to other icy bodies (d/D≅0.1), Ariel's complex craters with D≳ 35 km appear shallower than expected when compared to other icy moons [3], and its largest observed craters, Domovoy and Yangoor, are both much shallower than even this already shallow d/D trend would predict [1,3]. Yangoor (D=80 km) has a complex morphology and geologic history (Fig. 1). Roughly one-third of the crater rim has been disrupted by a combination of tectonism (an extension of Kewpie Chasma) and, potentially, cryovolcanism [1]. Yangoor's observed depth is 0.5–1.5 km, or roughly half its expected depth of ~2.7 km [3]. Schenk and McKinnon [4] also identified six craters in smooth terrain with diameters of 8–12 km that are 50–80% shallower than expected. Taken together, these observations suggest that some of Ariel's craters have been modified by viscous relaxation [1,2,3,4], in which the stresses induced by gravity on the crater's topography result in viscous flow that reduces crater depth. Viscous relaxation has been observed on icy moons such as Ganymede [5,6,7], Enceladus [8,9], Dione and Tethys [10]; however, the process would require Ariel's ice shell to have a relatively low viscosity, either due to warm temperatures or compositional effects.

Despite these observations, given the sparsity of the data, other explanations for Yangoor's shallow depth cannot be discounted. Very little, if any, of Ariel's ancient surface remains, and if cryovolcanic resurfacing was the culprit, Yangoor, Domovoy, and other shallow craters may simply be partly filled with cryovolcanic material.

Simulating Viscous Relaxation of Yangoor Crater: To assess the conditions required to substantially reduce Yangoor's depth by viscous relaxation, we used the finite element model Tekton [11] to simulate its evolution under a range of thermal and rheological conditions. We begin with an axisymmetric finite element mesh (i.e., only half the crater is simulated) that includes an 80-km diameter crater with an initial depth of 2.67 km (rim to center) at the surface. The depth is consistent with the depth-diameter curve of [3]. The simulations are viscoelastic and include dislocation creep (three mechanisms), diffusion, grain-boundary sliding, and basal slip in a composite flow law [12]. The thermal structure (surface temperature and heat flux) is set through the viscosity structure, and time dependent conditions can be simulated. Our current results use a surface temperature of 80 K, which is just cooler than peak polar temperatures from *Voyager 2* thermal emission measurements [13]. This temperature may be optimistically warm, as temperatures can fall to 30 K during the long polar night [14]. However, a solid-state greenhouse may buffer this variation and increase diurnally averaged temperatures by 20 K [14]. We investigated both radiogenic and constant heat fluxes for time spans of up to 4 Gyrs.

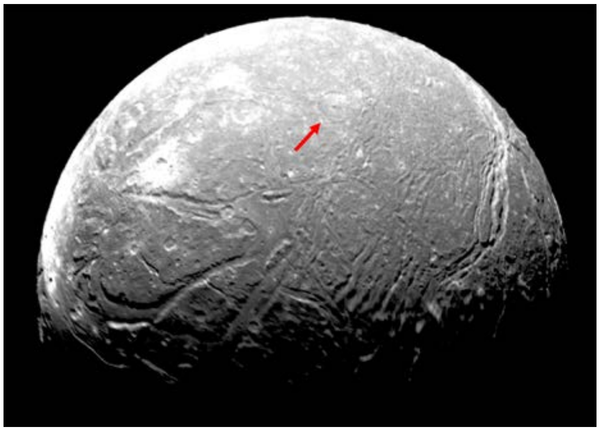

Figure 1: Voyager 2 mosaic of Ariel (https://photojournal.jpl.nasa.gov/jpeg/PIA01534.jpg). Red arrow indicates location of Yangoor crater.

Results: Radiogenic heating alone is insufficient to reduce the depth of Yangoor. We assumed a chondritic abundance [15] that results in a maximum radiogenic heat flux of 6.4 mW m^{-2} at 4.6 Gyrs ago, and 0.8 mW m^{-2} at present. Even after 4 Gyrs, the rim depth of our simulated crater changed by less than 8 m. A factor of two difference in the flux (e.g., due to greater or lesser abundance of radiogenic material) does not change the conclusion that radiogenic heating is inconsequential.

Reducing Yangoor's depth to within the range reported by [3] requires a sustained heat flux of at least 60 mW m^{-2} (Fig. 2): ten times the maximum radiogenic flux. In that case, the elevated flux must be sustained for 2 Gyrs. Higher heat fluxes sufficiently reduce Yangoor's depth on shorter timescales. A heat flux of 70 mW m^{-2} will reduce the depth to 1.5 km in 200 Myrs, and a flux of 80 mW m^{-2} will do so in 20 Myrs.

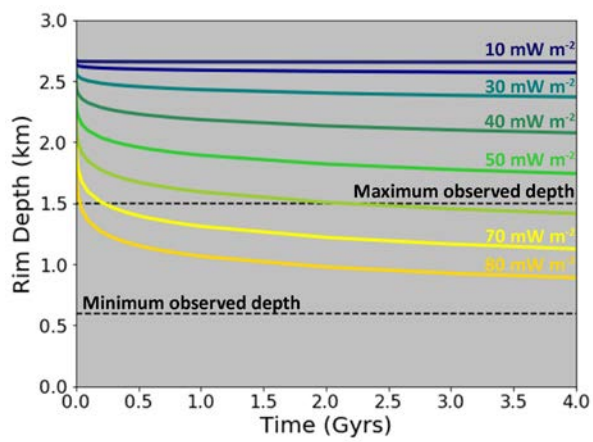

Figure 2: Rim depth as a function of time for a Yangoor-like crater under heat fluxes ranging from 10 mW m^{-2} to 80 mW m^{-2}, as labelled.

Discussion: The heat flux required to viscously relax Yangoor to a depth of < 1.5 km greatly exceeds radiogenic but is consistent with the range inferred by [16]. Tidal heating of Ariel may have occurred during its chaotic evolution through a series of mean-motion resonances [17,18,19]. These include a possible 4:1 mean-motion commensurability with Titania that would have increased Ariel's eccentricity to a value more than ten times its current eccentricity, with a damping timescale of 100 Myrs [19]. The timescale is sufficient to cause relaxation of Yangoor to its current depth, but the resulting heat flux is likely insufficient [16]. Viscous relaxation of Ariel's smaller craters is even more challenging and would require ever greater fluxes and/or longer timescales.

Alternatively, the viscosity and/or thermal conductivity of Ariel's lithosphere may be lower than assumed here. Ground-based observations have observed both CO_2 [20] and ammonia [21] on Ariel. CO_2 clathrate (notably *not* observed by [20]) has a much lower thermal conductivity than water ice [22] and would act to keep subsurface temperatures much warmer for the same heat flux. Unfortunately, they also have a high viscosity, and if present in quantities large enough to affect the thermal structure may inhibit viscous flow. Alternatively, a high-porosity ice layer, if sustained against closure by viscous flow, could also decrease the thermal conductivity and maintain a relatively warm lithosphere without increasing its viscosity.

Ammonia dihydrate is up to four orders of magnitude less viscous than water ice for temperatures greater than 143 K [23], and its presence might enable viscous relaxation [1,2], as also proposed for Enceladus [8]. However, at temperatures below 143 K, ammonia dihydrate is stronger than water ice [23] so a relatively warm subsurface is still required even if ammonia is invoked. Ongoing work will better constrain the compositional conditions that enable viscous relaxation at lower heat fluxes.

Acknowledgments: This work is supported by NASA's Solar System Workings Program (80HQTR20T0042 and 80NM0018F0612).

References: [1] Croft S.K. and Soderblom L.A. (1991) In: *Uranus*, Bergstralh, Miner, Matthews (Eds.), U. Arizona Press. [2] McKinnon W.B. et al. (1991) In: *Uranus*, Bergstralh, Miner, Matthews (Eds.), U. Arizona Press. [3] Schenk P.M. (1989) *JGR*, 94, 3813-3832–1345. [4] Schenk P.M. and McKinnon W.B. (1988) *AAS DPS*, Abstract #39.04. [5] Shoemaker E.M. et al. (1982) In: *Satellites of Jupiter*, Morrison (Ed.), U. Arizona Press. [6] Singer K.N. et al. (2018) *Icarus* 306, 214-224. [7] Bland M.T. et al. (2017) *Icarus* 296, 275-288. [8] Passey, Q.R. (1983) *Icarus* 53, 105-120. [9] Bland M.T. et al. (2012) *GRL* 39, L17204. [10] White, O.L. (2017) *Icarus* 288, 37-52. [11] Melosh H.J. and Raefsky A. (1980) *Geophys. J. R. Astr. Soc.* 60, 333-354. [12] Durham W.B. and Stern, L.A. (2001) *Annu. Rev. Earth Planet. Sci.* 29, 295-330. [13] Hanel, R. et al. (1986) *Science* 233, 70-74. [14] Veverka J. et al. (1991) In: *Uranus*, Bergstralh, Miner, Matthews (Eds.), U. Arizona Press. [15] Kirk, R.L. and Stevenson, D.J. (1987) *Icarus* 69, 91-134. [16] Peterson G. et al. (2015) *Icarus* 250, 116-122. [17] Tittemore W.C. and Wisdom J. (1988) *Icarus* 74, 172-230. [18] Tittemore W.C. and Wisdom J. (1990) *Icarus* 85, 394-443. [19] Tittemore W.C. (1990) *Icarus* 87, 110-139. [20] Grundy W.M. et al. (2003) *Icarus* 162, 222-229. [21] Cartwright R.J. et al. (2020) *ApJL* 898, L22. [22] English N.J. and Tse J.S. (2009) *Phys. Rev. Lett.* 103, 015901. [23] Durham, W.B. et al. (1993) *JGR* 98, 17667-17682.