FORMATION OF CORONAE ON MIRANDA BY CONVECTION DRIVEN RESURFACING. Noah P. Hammond and Amy C. Barr, Department of Geological Sciences, Brown University, Providence, RI 02910; noah_hammond@brown.edu

Introduction: Miranda, an icy moon of Uranus, is one of the most visually striking and enigmatic bodies in the solar system. Despite its relatively small size, (*R*=236 km), Miranda experienced an episode of intense resurfacing, resulting in the formation of three large "coronae" which dominate its surface [1].

Coronae have a perplexing morphology and are unique among surface features observed on the icy satellites. Each corona is ~200 km in diameter and has a polygonally shaped inner region composed of smooth plains or intersecting ridges surrounded by an outer belt of sub-parallel ridges and troughs [1]. Two possible formation mechanisms for coronae are silicate material sinking through an icy mantle causing concentric surface contraction [2]; and diapiric upwellings [3, 4] that cause extensional tectonics and spreading [5].

We simulate convection in Miranda's ice shell to test the hypothesis that coronae formed by convection-driven resurfacing during an episode of tidal heating. We use the model CitcomS [6] to simulate convection in a three-dimensional spherical shell representative of Miranda's ice mantle. We show that convection in an ice shell with a weak upper surface can simultaneously match the estimated heat flow, deformation pattern and corona distribution, for a reasonable range of internal structures, viscosities and heating rates.

Background: The outer belts of the coronae have been described as a type of ridge and trough terrain [7], a landform observed on many icy satellites including Ganymede, Europa and Enceladus. Ridge and trough terrain might be produced by a variety of tectonic and volcanic mechanisms [8]. Convection in an ice shell weakened by tidal flexing is one formation mechanism that is consistent with the extrodinarily high heat flux observed at the Enceladus South Polar Terrain [9].

Prior work suggests that coronae likely formed by a combination of extensional tectonics and volcanism. The outer belt of Arden corona is likely composed of tilt-block style normal faults [5] which may have a listric geometery [10]. The relatively smooth outer belt of Elsinore corona is suggested to form by a combination of extensional tectonics, fissure volcanism, and viscous flows [3, 11]. Inverness corona, characterized by a large bright cheveron bounded by dark bands, may be similar in structure to mid-ocean ridge triple junctions on Earth [12]. Each of these morphologies could be consistent with convection as a driving force.

Miranda's coronae also may be arranged in a skewed tetrahedral geometry, a pattern that can arise in convecting mantles with low viscosity contrasts [13]; the approximate centers of Arden and Elsinore corona are separated by ~120º, and both are ~60º from Inverness corona. Lithospheric flexure along the flanks of Arden corona suggests an elastic thickness of 2 km and a thermal gradient of 8 – 20 K/km during corona formation [5], cooresponding to a heat flux of $F = 24 – 60$ mW/m^2 for a thermal conductivity $k = 3$ W/m-K.

Methods: We use the 3D spherical convection model CitcomS [6] to simulate convection in Miranda's ice shell for a wide range of internal structures, surface viscosities and heating rates to determine whether convection can match the estimated heat flow, deformation pattern and distribution of coronae.

We assume Miranda is at least partially differentiated with a core size of $x=R_{core}/R_{satellite}$=0.25, 0.4, 0.55. The Rayleigh number,

$$Ra = \rho_i g \alpha \Delta T D^3 / \kappa \eta_1,$$

governs the vigor of convection, where ρ_i = 920 kg/m^3 is the density of ice, g=0.083 m/s^2 is gravity, $\alpha=10^{-5}$ K^{-1} is thermal expansivity, ΔT =160 K is the temperature contrast between surface and the base of the ice shell, $D = (1 - x)R_{satellite}$ is the ice shell thickness, $\kappa= 10^{-6}$ m^2/s is the thermal diffusivity and $\eta_1=10^{13}$ – 10^{16} Pa s is the viscosity of ice at the base.

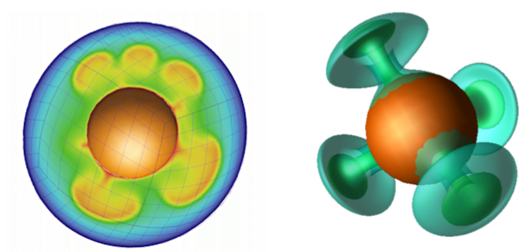

Figure 1: Simulation of convection in Miranda's ice mantle with x=0.4, Ra=$10^{6.5}$, $\Delta\eta=10^3$, started from quasi-random initial temperature purtabations. (left) Cross section of ice shell shortly after initial condition. Color denotes temperature, ranging from 60 – 220 K. (right) 3D view of convection after the heat flow approaches steady state. Colors show temperature iso-surfaces at T=100 K (blue) and T=140 K (green). Orange shows the core/mantle boundary.

We treat the mantle as viscous ice deforming by Newtonian volume diffusion [14]. We assume the viscosity contrast across the ice shell $\Delta\eta=10^3$ – 10^4 [9, 15], allowing sluggish lid convection to occur [16]. This simple model is a necessary first step for determining if convection driven resurfacing is a viable mechanism on Miranda. We perform simulations for Ra=10^5 –10^8 with a resolution of $64 \times 64 \times 64$ elements in each of the 12 spherical caps. Most of our simulations are basally heated and have an initially conductive temperature profile with a small shperical harmonic temperature pertabation near the base of $l=3$, *m=2*. We also explore the effect of random initial temperature perturbations and uniform internal heating.

Simulations are considered successful if they form tetrahedrally arranged, ovoidal shaped regions of surface extension, within which the average heat flux matches that inferred from flexure [5]. Model heat flux $F = k\frac{\Delta T}{D}Nu$, and Nu is the Nusselt number. Simulations are run until *Nu* approaches a steady state value.

Results: We find that convection can produce surface heat fluxes and deformation patterns consistent with Miranda's coronae for a limited range of internal structures and Rayleigh numbers. For a core fraction x=0.4, $\eta_1=10^{13} – 10^{15}$, $\Delta\eta=10^3 – 10^{3.5}$, and basal heating, a steady state tetrahedral convective pattern develops in which regions of surface extension have an average surface heat flux of 20 – 100 mW m^{-2}. Larger core fractions, viscosity contrasts and Rayleigh numbers generally lead to higher order convective patterns, where the number of plumes increases as a function of each of these variables.

We find that the initial temperature perturbation does not dominate the convection geometery. Figure 1 shows the results of convection with a high order, random temperature perturbation which still evolves to a steady state tetrahedral pattern, suggesting the core size, Rayleigh number and viscosity contrast are more important in determining the convection geometry.

Figure 2 shows the results of a simulation run with a uniform internal heat source in the ice shell of 0.9 GW. Regions of high heat flow and surface extension bear a striking resemblance to the shape and distribution of coronae, with heat flows comparable to that predicted from flexure [5].

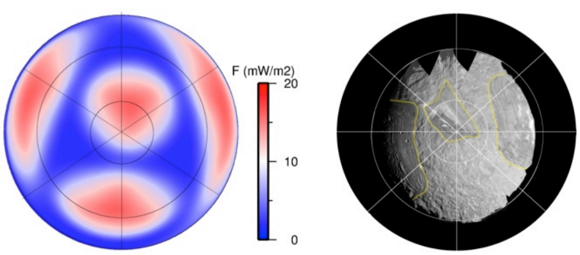

Figure 2: (left) Surface heat flux of a spherical convection simulation with a uniform internal heat source of 0.9 GW, x=0.55, Ra=$10^{6.5}$, $\Delta\eta=10^3$. Surface projection is lambert equal area. (right) Mosaic of Miranda constructed with Voyager 2 images. Yellow lines outline corona boundaries. Both images have the same projection.

Discussion: We show that if the viscosity contrast across Miranda's ice shell is low, convection will naturally produce the deformation pattern and distribution of coronae, while simultaneously matching the estimated heat flow.

The thermal energy required to drive convection is unlikely to be supplied by radiogenic or accrectional heating, due to Miranda's small size and low silicate fraction ($\bar{\rho}$=1.2 g/cm^3 [17]). However, Miranda's high inclination suggests it likely passed through an orbital resonane [18]. Tittemore and Wisdom [19] argue that Miranda passed through a 3:1 resonance with Umbriel, during which time Miranda's eccentricity may have reached 0.05. We use the tidal model of Meyer & Wisdom [20] to estimate that the equilibrium tidal heating rate during such a resonance is 0.3 GW.

We suggest that the energy released during coronae formation may have been an order of magnitude larger than the equilibrium heating rate, analogous to the high present heat flow of Enceladus, which is ~100 times higher than its equilibrium rate [20]. A total power of 1 – 10 GW would be consistent with the heat flow expected during coronae formation. This suggests that Miranda may have been active for only a portion of its time spent in resonance. Additionally, a low $\Delta\eta$ may be expected during such a resonance if near surface ice is weakened by tidal flexing and fatigue. Such a mechanism may lower the yield stress of ice and allow thermal buoyancy stresses to deform the surface [21].

Conclusion: We show that convection driven resurfacing is consistent with the orbital history of Miranda, the estimated heat flow from flexure, and the deformation pattern and distribution of coronae. However, one difficulty is that Miranda may be hard to differentiate and convection and corona formation may have occurred while Miranda was undergoing partial differentiation [3, 5]. We are exploring this scenario.

Acknowledgements: This work is supported by NASA NESSF fellowship NNX13AN99H.

References: [1] Smith B.A. et al., *Science* 233, 43-64. 1986 [2] Janes D. M. and H. J. Melosh, *JGR* 93, B4 3127-3143, 1988 [3] Johnson T. V., et al., *Sci. Amer.* 256, 48-60, 1987 [4] Greenberg R. et al., in *Uranus*, 693-735, 1991 [5] Pappalardo R. T., et al., *JGR* 102 E6 13369-13379, 1997 [6] Zhong S., M. T. Zuber, L. Moresi and M. Grunis, *JGR* 105, B5 11063-11082 2000 [7] Pappalardo R.T., *Ph.D dissertation*, 1994 [8] Pappalardo R.T. and R. Greeley 1995, *JGR* 100, 18995-19007, 1995 [9] Barr A. C. *JGR* 113, E07009, doi:10.1029/2008JE003114, 2008 [10] Beddingfield C. B., et al., *LPSC XLIII* 1366, 2012 [11] Schenk P. M., *JGR* 96, 1887-1906, 1991. [12] Gonzalez A., AGU-EUG Joint Assembly, 7393, 2003 [13] Ratcliff J. T., G. Schubert and A. Zebib, *JGR* 101, B1 25473-15484, 1998 [14] Goldsby D. L. & Kohlstedt D. L. *JGR* 106, p. 11017-11030, 2001 [15] Hammond N. P. & A. C. Barr, *Icarus* 227, 206-209, 2014 [16] Solomatov V. S., Phys. of Fluids, 7, 266, doi:10.1063/1.868624, 1995 [17] Jacobsen R. A., et al., *Astro. J.* 103, 6, 1992 [18] Dermott S. F., et al., *Icarus*, 76, 295-334, 1988 [19] Tittemore W. C. & J. Wisdom. *Icarus*, 85, 394-443, 1990 [20] Meyer J. & J. Wisdom, *Icarus* 188, 2 535-539, 2007 [21] Tackley P. J., *G^3*, 1, 1, 2003.