MIRANDA HEAT FLUX ESTIMATES FOR A LITHOSPHERE WITH AMMONIA HYDRATES. C. B. Beddingfield[1,2], R. J. Cartwright[1,2]. [1]Sagan Center at the SETI Institute, [2]NASA Ames Research Center.

Introduction: Previous heat flux estimates for Miranda are mysteriously high [1, 2] and do not fall within the range expected from likely energy sources (e.g., radiogenic heating, tidal heating from prior orbital resonances, etc.) [e.g., 3, 4]. These previous heat flux estimates assume icy lithospheres of pure H_2O ice. However, the mass fraction of ammonia for icy satellites is hypothesized to be about 15% for solar nebula condensation temperatures between 85 K and 130 K [5].

In support of this model, ground-based observations provide evidence for NH_3-hydrates on the surfaces of Miranda [6] and its neighboring satellite, Ariel [7, 8]. Therefore, it is critical to incorporate the presence of this constituent when performing geophysical calculations because the material properties, especially thermal conductivity, are substanially different than that of pure H_2O ice [9]. For example, mixtures with ammonia abundances of 10% to 30% exhibit thermal conductivities that range from two to three times lower than that of pure H_2O ice [9]. In this work, we estimate the heat flux of the Arden Corona region on Miranda during fault formation, taking into account a lithosphere that includes NH_3-hydrates.

Ammonia Hydrates on Icy Satellites: NH_3 was likely incorporated into the satellitesimals that formed the icy moons of the giant planets [e.g., 5, 10, 11, 12]. Accreted NH_3 ice would have reacted with other constituents, notably H_2O ice, to form NH_3-hydrate compounds, which should still be present within the lithospheres of these satellites. Moons with ongoing geologic resurfacing processes like Titan, Triton, and Enceladus, could possess briny liquid oceans with substantial fractions of NH_3-hydrates [13, 14, 15]. NH_3-hydrates have been detected on the surface of Enceladus [e.g., 16, 17], as well as in material spewing into space from its south polar jets [e.g., 18, 19].

Additionally, strong evidence for NH_3-hydrates has been detected in both ground-based reflectance spectra [20, 21, 22, 23] and New Horizons datasets of Charon [24, 25]. This constituent may have contributed to ancient cryovolcanism in Vulcan Planum on Charon [26]. NH_3-hydrates have also been detected on the Trans-Neptunian Object (TNO), Quaoar [27], and the Uranian satellites Ariel [7, 8] and Miranda [6].

NH_3-hydrates are efficiently removed from icy surfaces by charged particle bombardment [28 and references therin]. On the surfaces of TNOs, NH_3-hydrates are effectively removed by proton bombardment within a few 10's Myr [29], and this constituent would be removed over much shorter time periods for the magnetospherically-embedded moon Miranda. Therefore, any ancient deposits of NH_3-hydrates exposed on the surface of Miranda should have been removed over timscales much shorter than the age of the Solar System. However, subsurface deposits of NH_3-hydrates would be shielded from surficial irradiation and are presumably still present in the lithospheres of icy moons.

The presence of NH_3-hydrates in icy satellite lithospheres has important implications regarding their rheological properties, thermal properties, and geologic histories. NH_3-hydrates, mixed with H_2O ice, dramatically reduces the freezing temperature of the mixture compared to pure H_2O ice, as well as changing other rheological properties including viscosity [30, 31], and thermal conductivity [9]. The presence of NH_3-hydrates in the lithosphere of Miranda is a possible explanation for the outstanding mystery of why estimated heat fluxes are peculiarly high. As summarized in [4], contributions from tidal heating, radiogenic heat production, and other energy sources, are not significant enough to explain the high estimated heat fluxes of small and mid-sized icy satellites.

Thermal Gradient at the Time of Faulting: We take the scheme for calculating the thermal gradient and heat flow at the time of faulting from [1, 32, 33]. The temperature at the brittle-ductile transition depth can be found by equating the brittle strength of a material at the brittle-ductile transition depth with the ductile strength, and solving for temperature.

The brittle strength of a material, S, is given by

$$S = 2(\mu\sigma_3 + C)B, \quad (1)$$

where μ is the friction coefficient, σ_3 is the minimum compressive stress, C is the material's cohesion, and B = $(\mu^2 + 1)^{1/2} + \mu$, assuming randomly oriented fracture planes and no pore fluid pressure [34]. When the material is in horizontal tension,

$$\sigma_3 = \rho g z - S. \quad (2)$$

The brittle strength of an icy lithosphere under tensional stress is given by

$$S_{ten} = \frac{2(\mu\rho g z + C)B}{2\mu B + 1}, \quad (3)$$

where ρ is the ice density and g is gravity. For μ, we used the range of estimated values for cryogenic H_2O ice of $\mu = 0$ [35] and $\mu = 0.55$ [36]. We used C = 1 MPa [36], $\rho = 930$ kg m^{-3}, and g = 0.079 m s^{-2}. We also used the range of estimated Miranda brittle-ductile transition depth values for z of 6.7 to 9.0 km [1].

The ductile strength of water ice is given by

$$S_d = \left(\frac{\dot{\epsilon} d^p}{A}\right)^{\frac{1}{n}} \exp\left(\frac{Q}{nRT}\right), \quad (4)$$

where $\dot{\varepsilon}$ is the strain rate, A, p, and n are empirical constants, d is the grain size, Q is the activation energy of creep, R = 8.3145 J mol^{-1} K^{-1} is the gas constant, and T is the absolute temperature. We used the empirically derived NH_3-hydrate flow constants for a mole fraction ammonia dihydrate of 0.15, associated with pressures of 50 MPa and temperatures ranging from 143 to 176 K [30]. We used values of Q = 54.1 kJ mol^{-1}, A = 2.56 MPa^{-n} s^{-1}, and n = 5.63 [30]. In the case of superplastic flow, p = 1.4 [37], and for dislocation creep, p = 0 [38].

In our calculations, we used grain sizes ranging from d = 0.1 to 10 mm, consistent with grain size estimates for Europa's lithosphere [33, 39], since Miranda's grain sizes are unknown. For grain sizes of d = 0.1 and 1 mm, superplastic flow is the dominant creep mechanism, whereas dislocation creep is dominant for d > 1 mm [40, 41]. In our calculations, strain rates range from $\dot{\varepsilon} = 10^{-15}$ s^{-1}, which is an approximate strain rate of faults on Earth, and $\dot{\varepsilon} = 10^{-10}$ s^{-1}, which is the estimated mean value for tidally-induced strain rates on Europa ($\dot{\varepsilon} = 2 \times 10^{-10}$ s^{-1}) [42].

The thermal gradient is given by

$$\Delta T = (T_z - T_s)/z \,, \quad (5)$$

where T_z is the temperature at depth z and T_s is the surface temperature. We use T_s values of 70 K, the radiative equilibrium temperature of Miranda's surface [43], and 86 K, the measured subsolar brightness temperature for Miranda's surface [44].

Our calculation results show that the thermal gradient of Miranda's Arden Corona region was between 7 and 33 K km^{-1} at the time that faulting occurred. These results are similar to previous estimates of 6 to 25 K km^{-1} [1], and 8 to 20 K km^{-1} [45], which utilized the properties of pure H_2O ice in their calculations.

Heat Flux at the Time of Faulting: The thermal conductivity for H_2O ice with NH_3 abundances between 10% and 30% ranges from 1 to 2 Wm^{-1} K^{-1} at the estimated surface temperatures of the Uranian satellites [9]. Using this thermal conductivity range, the heat flux is given by

$$F = k_c \left(\frac{T_z - T_s}{z}\right) \,. \quad (6)$$

Our results show that Miranda's heat flux in the Arden Corona region was between 7 and 66 mW m^{-2} during fault formation. Previous estimates, that assumed a pure H_2O ice lithosphere, were between 31 and 112 mW m^{-2} [1], and between 40 and 100 mW m^{-2} [2]. Thus, our heat flux calculations are significantly lower than previous results.

Future Work: We will compare our heat flux results to values expected from likely energy sources (e.g., radiogenic heating, tidal heating, etc.). In addition, we will investigate NH_3-hydrate surface abundances on icy satellites in the Saturnian, Uranian, and Pluto-Charon systems to better estimate their lithospheric heat fluxes. We will then perform geophysical calculations to estimate heat fluxes using various methods that incorporate the morphology of tectonic features on these icy bodies.

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