MODELING METEORITE HEAT TRANSFER IN AN ANTARCTIC ENVIRONMENT. William J. Oldroyd[1], Jani Radebaugh[2], Denise Stephens[1], Ralph D. Lorenz[3], Ralph P. Harvey[4] and James Karner[5]. [1]Department of Physics and Astronomy, Brigham Young University, Provo, UT (will.oldroyd@gmail.com) (denise_stephens@byu.edu). [2]Department of Geological Sciences, Brigham Young University, Provo, UT (janirad@byu.edu). [3]Johns Hopkins University Applied Physics Laboratory, Laurel, MD (ralph.lorenz@jhuapl.edu). [4]Department of Earth, Environmental and Planetary Sciences, Case Western Reserve University, Cleveland, OH (rph@case.edu), [5]Department of Geology and Geophysics, University of Utah, SLC, UT (j.karner@utah.edu).

Introduction: Meteorites are essential tools for understanding early Solar System dynamics, composition and formation [1, 2, 3]. They developed early on and are one of the only remaining clues to the compositions and textures present in the early Solar System. Models used to determine abundances of materials available in the early Solar System for planetesimal formation rely on meteoritic composition [4]. They also rely on the relative abundance of samples collected, since this may reflect the overall populations of different near-Earth asteroids, and therefore materials available for formation in this neighborhood [4, 5]. Antarctic meteorites appear to reflect the overall abundance of available materials in the near-Earth environment [1], with the exception of meteorites with high specific gravities, such as irons. These appear to be underrepresented in ANSMET (Antarctic Search for Meteorites Program (Fig. 1)) collections over the last 40 years. This underrepresentation in the Antarctic suite is in contrast with observed meteorite falls, which are believed to represent the actual population of meteorites striking Earth [5].

The solution to this discrepancy may rest in the fate of meteorites once they have landed on the Antarctic ice sheet. Dark meteorites sitting on the bright Antarctic ice absorb solar flux, causing them to heat above the melting point of water ice, even in the ultra-cold environment, possibly leading to downward tunneling into the ice (Fig. 2).

Figure 1. An ordinary chondrite collected in Antarctica as part of ANSMET. Note the dark fusion crust.

The descent of the meteorites downward through the ice is counteracted by upward ice sheet flow that supports the meteorites, coupled with ablation of surface snow and ice near mountain margins, which helps to force meteorites towards the surface. Meteorites that both absorb adequate thermal energy and are sufficiently dense may reach a shallow equilibrium depth as downward melting overcomes upward forces during the Antarctic summer [6]. Using solar flux data we collected during two seasons in the Antarctic deep field (2013-14 and 16-17), we are mathematically modeling the thermal interactions of meteorites with their Antarctic environment in response to solar heating accounting for a wide range of parameters.

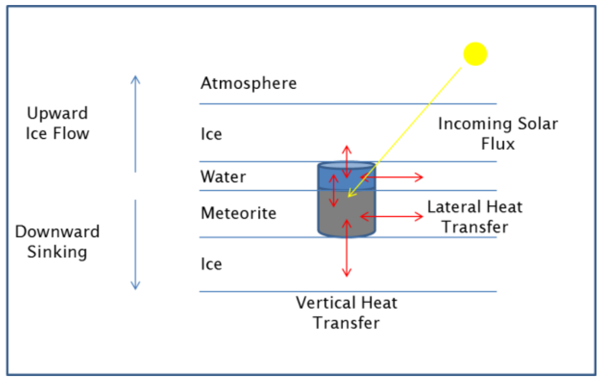

Figure 2. Energy transfer in the meteorite ice system. Not to scale. (This figure is an adaptation of Fig. 3 in Evatt et al., 2016 [6]).

Observations: Using a pyranometer, we obtained solar flux measurements at varying depths in two deep field sites in Antarctica, the Miller Range (2013-14) and Elephant Moraine (2016-17). During the 2013-14 meteorite collection season we measured the light level at depths of 0, 20, and 45 cm after snowfall and aeolian transport gradually buried the detector. For the 2016-17 season depths of 0 and 30 cm were observed. These data give insight into the effect of snowfall on solar flux received by subglacial meteorites. For example, a snow covering of 30 cm corresponded to an approximately 80% drop in light level. We are currently analyzing the data to determine how much energy can be absorbed by various types of meteorites at different depths, including the effect of snow cover (Fig. 3).

Models: The results of our measurements are used to determine the amount of thermal energy absorbed by meteorites and their surroundings. Expanding on the one-dimensional model put forth by Evatt et al., 2016 [6], we modeled a sample meteorite using 3D cylindrical heat transfer in typical Antarctic conditions. Our model accounts for incoming solar energy absorbed as a function of albedo, surface area of the absorbing face, and total incident solar flux (which is measured light level, as in Fig. 3, times a calibration factor) (eq.1); radiative heat transfer between the meteorite and the ice as a function of their temperatures, emissivities and the surface area of the absorbing face (eq.2); vertical conductive heat transfer as a function of temperature, depth, vertically oriented area and thermal conductivity (eq.3); and lateral conductive heat transfer assuming cylindrical symmetry as a function of temperature, distance from the meteorite, thermal conductivity and meteorite height (eq.4) as well as various other parameters. Assuming cylindrical symmetry greatly simplifies lateral heat transfer calculation. The incoming heat from solar radiation is transmitted vertically and laterally both through conduction and radiation (eq.5) (See Fig. 2).

$$Q_{in} = (1-\alpha)AS_0 \quad (1)$$

$$Q_{rad} = \frac{\sigma(T_1^4 - T_2^4)A}{\frac{1-\epsilon_1}{\epsilon_1}+\frac{1-\epsilon_2}{\epsilon_2}+1} \quad (2)$$

$$Q_z = -\kappa A \frac{\partial T}{\partial z} \quad (3)$$

$$Q_r = 2\kappa\pi l \frac{T_1 - T_2}{\ln(r_2/r_1)} \quad (4)$$

$$Q_{in} = Q_{rad} + Q_z + Q_r \quad (5)$$

We note that incoming solar radiation measured is directly proportional to energy absorbed, hence, a drop in light measured is an equal percentage drop in energy (eq.1). Our model utilizes appropriate values for incoming solar energies at Antarctic latitudes (around 300 W/m^2), starting temperatures (typically -20°C in summer), and typical physical and thermal properties of various species of meteorites collected by ANSMET. In addition to our heat transfer models, we employ a melting threshold model as described in Lorenz 2012 [7] to determine under which circumstances melting occurs, that is, when the emitted heat and the base temperature of the ice exceed the melting temperature (eq.6) (This is equation 2 in Lorenz 2012 [7]).

$$T_0 + \frac{q}{4\pi kR} > T_m \quad (6)$$

The incorporation of more complex meteorite geometry, lateral heat transfer, and snowfall is employed to expand upon the model put forth in Evatt et al., 2016 [5] with which we compare our results.

Experiments: Additionally, we are conducting solar flux measurements under varying thicknesses of ice and snow, both in a controlled laboratory environment and at local analogue sites in the Rocky Mountains. We are using simple solar cells to improve the quality and accuracy of our measurements [8]. We are also using similar-sized objects of varying density and albedo to evaluate the effect these parameters have on thermally-induced sinking.

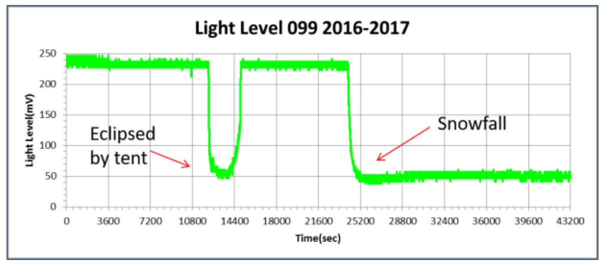

Figure 3. Light level measured across the time of snowfall. A snowfall event of 30 cm causes a large drop in light level (about 80%). It is preceded by another drop where a tent blocked the sensor from direct sunlight.

Conclusions and Implications: We are modeling the thermal response of a meteorite on the Antarctic ice from incoming solar radiation to determine if heavy meteorites can tunnel downward through the ice. That snowfall of just 30 cm results in an 80% drop in solar energy has implications for preserving meteorites under a blanket of snow, which has occurred in many locations in the Antarctic deep field in recent years. The discovery of missing or additional meteorite populations would change our estimates of primeval solar system composition ratios [4]. Our solar flux data may also be useful in determining the environmental limit for photosynthetic extremophiles in icy habitats [9].

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