CERES SURFACE THERMAL INERTIA: PREDICTIONS FOR NEAR-SURFACE WATER ICE STABILITY AND IMPLICATIONS FOR PLUME GENERATING PROCESSES.

T. N. Titus, [1]USGS Astrogeology Science Center, 2255 N. Gemini Dr., Flagstaff, AZ 86001 (ttitus@usgs.gov).

Introduction: Recent observations suggesting H_2O vapor plumes above the surface of the dwarf planet Ceres [1] have led to discussions concerning their formation processes. Two hypotheses have been proposed: (1) cryo-volcanism where the water source is the mantle and the heating source are long-lived radioisotopes [2] or (2) comet-like sublimation where near-surface water ice is vaporized by seasonally increasing solar insolation [1-3]. This abstract introduces a third process, involving cryo-magmatism that brings liquid water close to the surface. The water freezes, recharging near-surface ice. In this scenario, increasing solar insolation would be the final trigger that initiates sublimation and the observed plumes. This third mechanism also shows how cryo-volcanism and near-subsurface sublimation are not necessarily mutually exclusive; all three processes could be active on Ceres.

Background: Asteroid 1 Ceres (hereafter referred to as Ceres) is the largest asteroid in the Main Asteroid Belt (MAB) and, in 1801, was the first MAB object to be discovered [4]. Several researchers have suggested that Ceres is a differentiated body with an icy mantle and a rocky inner core [2, 5-6]. The bulk density for Ceres is 2100 kg/m^3, suggesting a total water content between 17% and 27% by mass [6]. The oblate spheroid shape with a major and minor axis of 487.3 (±1.8) km and 454.7 (±1.6 km) suggests a non-homogeneous body [5]. It has been suggested that the lack of a dynamical family or meteorites from Ceres (such as the ones that exist for Vesta [7,8] and Pallas [9]) is due to a water-ice-rich near-surface composition; ejecta from impacts into Ceres would be largely composed of ice that either sublimes or vaporizes (e.g. [10]).

Ceres' orbit is both eccentric and inclined to the ecliptic. Its obliquity is quite low (~3º), so seasonal changes on Ceres will be due to changes in solar distance and not due to the minor changes in the solar declination. This also suggests that there should be a great deal of symmetry in surface and near-surface properties between the two hemispheres.

Observed Plumes: Evidence of water plumes has been observed by [1] and [2], albeit the 1991 detection was marginal. The observations by [1] suggested that the water vapor detected was produced by plumes producing around 10^{26} molecules per second (or 3 kg/s). The source of the plumes appeared to be localized to the mid-latitudes. Based on their observations of water vapor, the sub-earth point at the times of observations, and a map of Ceres from near-infrared adaptive-optics imaging observations, [1,11] have suggested two sources for the venting, "Piazzi" (longitude, 123º, latitude +21º) and Region A (longitude 231º, latitude +23º).

[1] favored the comet-like sublimation model as all observed plume activity to date has occurred on the perihelion half of Ceres' orbit. We use a simple 1-D thermal model to test the possibility that either "Piazzi" or Region A could be the source of the vapor plumes without active cryo-volcanism.

Thermal Modeling: Thermal inertia is the thermal property of a material to resist change in temperature. This resistance may be due to a high heat capacity, high density, and/or high thermal conductivity. Thermal inertia is defined as $I = \sqrt{k\rho c}$, where k is thermal conductivity, ρ is density, and c is heat capacity. SI units for I are J m^{-2} s$^{-1/2}$ K^{-1} which henceforth will be referred to as ''TIU'' (thermal inertia unit) as proposed by Putzig [12]. The surface of Ceres is expected to have low to medium thermal inertia values. Most of the estimated values range between 15 and 38 TIU [15, 16], but other studies have suggested values as high as 80 TIU [13] (derived a thermal inertia of 80 TIU using IRAS data) and as low as 12.6 TIU [14] (used polarimetry).

We employ a multi-layered thermal-diffusion model called 'KRC' [17-19], which has been used extensively in the study of martian thermo-physical properties (e.g. [17, 20]). This numerical model was easily modified for use with Ceres by replacing the martian ephemeris with the Ceres ephemeris and turning the atmospheric effects off. This model does not allow for time-variations in subsurface properties due to diffusion of water, nor does it consider the effects of sublimation of H_2O. Since the focus of this study was to determine locations where H_2O ice would be stable over the life-time of the solar system, the effects of H_2O sublimation and diffusion could be neglected. This model calculates surface temperatures throughout an entire Ceres year for a specified set of slope, azimuth, latitude, elevation, albedo and thermal-inertia. For this study, model runs were conducted using a range of thermal inertia from 11 to 42 TIU. Two effective emissivities, ε, were used, 0.9 to simulate a smooth surface and 0.7 to simulate a rougher surface. A constant density of 1250 kg/m^3 where used for all runs. This density is an average density based on the lunar regolith. A constant Bond albedo of 0.03 [21] was used for all models. The effect of changing the Bond Albedo by ~10% (0.028-0.032) [21] was examined but this changed the surface temperatures by only a fraction of a degree.

Thermal Model Results: Once the surface temperature has been calculated for both the diurnal and annual cycles, the near-surface temperature can be estimated by calculating the annual mean temperature. This would be the temperature of the near surface below a few annual skin depths.

The exact latitude for the snowline (the term we are using to designate the latitude at which a near-surface ice table becomes thermally stable at a depth of about five annual skin depths.) is dependent on thermal inertia, surface albedo, surface emissivity and surface topography and roughness. Of these parameters, thermal inertia and effective emissivity (a combination of surface emissivity and roughness) are the least constrained and will have the greatest impact on the location of the snowline. At the edge of the snowline is a zone where the deeper subsurface (below 5 annual skin depths) remains at or below H_2O ice the stability criteria of 145 K [21] but at intermediate depths (about 1 annual skin depth), the seasonal thermal pulse might be sufficient to mobilize the water ice.

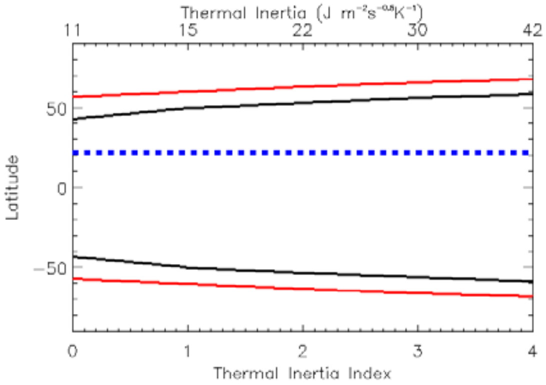

Figure 1: Black contours mark the zonal snowline for ε=0.9; the red marks ε=0.7. The thick dashed blue line marks the latitudes for "Piazzi" (123°, +21°) and Region A (231°, +23°) identified by [1] as possible sources for the observed plumes.

While other external conditions might be needed, such as a small meteor impact, to initiate an actual plume of water vapor, this narrow latitude zone is the most favorable for seasonal comet-like sublimation. Fig. 1 compares the zonal (latitude) snowline for long-term near subsurface ice stability based on the temperature criteria of an annual mean of 145 K or less [22]. The snowline is restricted to pole-ward of 40 degrees for even low thermal inertia smooth body models. This result is not consistent with "Piazzi" or Region A being the source of the plumes as identified by [1], unless some form of cryo-volcanism (or cryo-magmatism) is invoked.

Cryomagmatic Model: One possible model is for cryo-magmatism to recharge the near-surface with water. If the intrusion occurs during the aphelion half of the orbit, the ground will be cold and the water will quickly freeze. As Ceres approaches perihelion, solar radiation warms the surface, causing a thermal pulse to penetrate the near-surface. Once the thermal pulse reaches the ice, sublimation is initiated. A schematic of this is shown in Fig. 2.

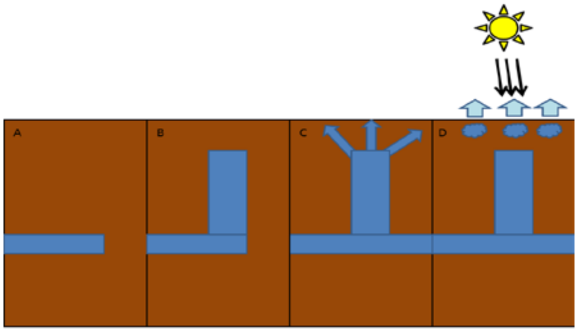

Figure 2: A simple schematic illustrating the near-surface being recharged via cryomagma (A-C) and the later sublimation being imitated by increased insolation (D).

Conclusion: Comet-like sublimation is unlikely to occur in the equatorial and mid latitudes since near-surface ice is not stable. Therefore, any plume activity originating from the non-polar regions is likely the result of some form of cryovolcanism, either to create the plume, or to recharge the ice table.

References: [1] Küppers et al. (2014) *Nature*, **505**, 525-527. [2] Castillo-Rogez & McCord (2010) *Icarus* **205**, 443–459. [3] A'Hearn & Feldman (1992) *Icarus* **98**, 54–60. [4] Piazzi (1802) *Philos. Mag*. **12**, 54–62. [5] Thomas et al. (2005) *Nature*, **437**, 224-226. [6] McCord & Sotin (2005) JGR, 110, E05009. [7] Binzel and Xu (1993) *Science*, **260**, 186-191. [8] DeMeo and Carry (2013) *Icarus*, **226**, 723-741. [9] Gil-Hutton, (2006) Icarus, 183, 93-100. [10] Rivkin et al., (2014) *Icarus*, **243**, 429-439. [11] Carry (2008) *Astron. Astrophys.* **478**, 235–244. [12] Putzig (*2006*) Ph.D. Dissertation [13] Keihm et al. (2013) [14] Johnson et al. (1983) [15] Spencer, J. (1990) , *Icarus* **83**, 27-38. [16] Chamberlain et al. (2009) [17] Kieffer et al. (1977) *JGR*, **82**, 4249-4291. [18] Kieffer (1979) *JGR* **84**, 8263-8288. [19] Kieffer (2013) *JGR* **118** 451-470. [20] Titus et al., 2003, *Science* **299**, 1048-1051. [21] Li et al., (2006) *Icarus*, **182**, 143-160. [22] Schorghofer (2008) *Ap. J.* **682**, 697-705.