VISCOUS RELAXATION ON COMETS. A. F. Cheng and A. J. Dombard, The Johns Hopkins University Applied Physics Laboratory, Laurel, MD, 20723, USA.

Introduction: Comets are icy remnants from the epoch of planet formation. Jupiter family comets (JFCs) are thought to have formed beyond Neptune and to have been transported recently to their current orbits, a journey requiring several million years [1-3]. These objects are JFCs for only a brief time at the very end of their existence, lasting at most ~10^4 yr owing to mass loss, fragmentation, and orbital evolution.

There have been spacecraft encounters with three JFCs from which images have sufficient resolution to study surface morphology: P/Borrelly [4], P/Wild 2 [5], and P/Tempel 1 [6]. Borrelly measures ~8.0 × 3.15 km. Wild 2 is fitted to triaxial ellipsoid diameters of 3.30 × 4.00 × 5.50 km. The shortest and longest axes of Tempel 1 are ~4.9 km and 7.6 km. A striking observation is that impact craters could not be identified unambiguously, though images show a wealth of surface features. The surface of Tempel 1 is heavily modified. Perhaps the best crater candidates lay near the Deep Impact impact site [6], though these features are seemingly just remnant rims. Other circular depressions are present with a size distribution consistent with an impact population [6]. Depressions on Wild 2 have been tentatively identified as possible craters; the flat-floored, steep-walled morphologies do not resemble other planetary craters, although impacts into layered targets in the laboratory or into microscopic, strength-dominated targets have reproduced aspects of the Wild 2 depressions [5]. The general impression is that large-scale topography (hundreds of meters to kilometers) is muted on JFCs, while small-scale topography (tens to a hundred meters) is present with in some cases extremely steep (> 70°) slopes [5]. These observations suggest an evolutionary process that can soften large-scale terrain, can preserve small-scale topography, and potentially can modify the surface such that craters are rendered ambiguous. We propose viscous relaxation of cometary ice.

Relaxation may also serve to reduce an elongated nucleus to a more spherical shape. An expectation of a collisional population is that the members would be elongated [7]; however, ratios of longest to shortest axes of Tempel 1 and Wild 2 are < 2. Conversely, the range in this ratio of all three nuclei spans nearly the same range as resolved asteroids, so this piece of evidence is not compelling in of itself. Coupled with the observed terrain softening though, it is plausible that viscous relaxation may substantially modify both the shapes and cratering records of comets over the course of their orbital evolution and existence as a JFC.

Methods: To estimate timescales for terrain softening, we use the well known analytic solution for viscous relaxation of topography [e.g., 8]. This timescale is $4\pi\eta/\rho g\lambda$, where η is the (constant) viscosity, ρ is density (of order 1000 kg m^{-3}), g is the gravitational acceleration (of order 1 mm s^{-2}), and λ is wavelength. Viscosities are temperature sensitive, but the thermal structure of JFCs is complex, involving heat transfer from nonuniform sources (solar, radiogenic, latent) via sublimation/recondensation, vapor transport, intracavity radiation, and conduction in a layered, porous, nonspherical body [9], all beneath shallow (< 10 cm) diurnal variations of order 100 K in a thin, nonvolatile surface layer. Thus to facilitate our estimates, we neglect this thin surface layer and assume the nucleus is isothermal. The viscosity must satisfy the fluid constitutive relation between stress σ and strain rate $\dot{\varepsilon}$, $\eta = \sigma/3\dot{\varepsilon}$ (the factor of 3 results from a geometric normalization in creep experiments [10]); consequently, we need to estimate the driving stress. We assume this stress equals a topographic overburden of $\rho g\lambda/10$. Strain rate must also be calculated. We assume that creeping flow can be approximated by the flow of water ice. Solid-state flow in ice operates via a handful of creep mechanisms; the relevant parameters have been measured, except for diffusion creep, for which the parameters have only been estimated [11]. This lack of data is potentially problematic because at the low stresses and small grain sizes appropriate for comets, diffusion creep is expected to dominate [11]. Diffusion creep (and a grain-boundary-sliding mechanism) is grain-size sensitive. In the presence of a grain size distribution, the relevant size for a rough estimate of creep rate is the characteristic size of the load-bearing ice matrix, here assumed to be 0.1-1 μm.

The timescale for an elongated comet to become more spherical can be estimated as a ratio of the required strain to the creep strain rate. We assume a prolate spheroidal nucleus (similar arguments can be made for an oblate nucleus). Gravitation forces will seek to reduce the length of the long axis and increase the lengths of the equatorial axes. If the initial nucleus is some constant C longer than it is wide, the large strain is $\exp(1 - C^{-2/3}) - 1$. For comets 2-5 times as long as they are wide, this required strain is ~45-85%; here, we will use 75%. Because ice viscosity varies by orders of magnitude, our estimated timescales are not sensitive to this range in strain. To calculate strain rate, we must again estimate driving stress. The size range for the comets under consideration is 1-10 km. The product of this length scale with the density and gravity of comets yields an estimate of 1-10 kPa. Ice can be hardened by the inclusion of silicate particulates at volume fractions up to 0.56 (past which much slower silicate creep dominates, likely precluding relaxation on comets), effectively dropping the driving stress by up to a factor of ~3 [10]. Thus, we consider a stress range of 0.1-10 kPa. This range exceeds the inferred bulk tensile strength of comets of order 0.1 kPa [12]; however, a self-gravitating body with topography everywhere shallower than the local angle of repose can support gravitational stresses in excess of the bulk tensile strength.

Results: We show in Fig. 1a the relaxation timescale as a function of effective temperature, for several topographic wavelengths. Reasonable timescales can be achieved. For a timescale of 10^4 yr (lifetime of a JFC), topography with wavelengths of 1000, 100, and 10 m need temperatures of ~155, ~165, and ~175 K, for a grain size of 0.1 μm. For 1 μm, temperatures of ~190, ~200, and ~215 K are needed. For a timescale of 1 kyr, these temperatures increase to ~165, ~175, and ~190 K for 0.1 μm and ~200, ~215, and ~235 K for 1 μm. Though no direct data exists, models suggest temperatures within comets, below any diurnal or annual effects, may reach as high as ~200 K [9]; thus, it is conceivable that long wavelength topography can be relaxed, while shorter wavelength topography is preserved. Diffusion creep does indeed dominate the flow. So at a particular grain size and temperature, increasing (decreasing) the wavelength, and hence driving stress, by an order of magnitude translates into a decrease (increase) in the timescale by an order of magnitude. In addition, the effect of silicate hardening [10] can be estimated by shifting the curves towards the next lower wavelength (i.e., lower stress).

Timescales for an elongated comet to become more spherical are shown in Fig. 1b. Again, diffusion creep dominates, and reasonable timescales can be achieved. For a 10^4 yr timescale, the effective temperature needs to be ~140-155 K for a grain size of 0.1 μm and ~165-190 for a grain size of 1 μm. These temperature ranges cover the variations in the driving stresses, with lower stresses, and hence slower flow, necessitating higher temperatures. For 10^3 yr, temperatures of ~145-160 K are needed for a 0.1 μm grain size, ~175-205 K for 1 μm. The fact that Borrelly remains elongated suggests insufficiently high internal temperatures.

Discussion: This work has shown that *viscous relaxation of ice can alter the overall shape and kilometer-scale topography of the nuclei of JFCs* during their brief sojourns in the inner solar system. The specific wavelengths affected and the degree of modification could change from object to object or even from one part of an object to another. A creep rheology for crystalline water ice has been assumed, but the nature of cometary material is uncertain regarding composition and physical state – crystallinity, grain sizes, ice-dust ratio, porosity. The interplay of relaxation and other surface modifying processes remains to be assessed. In addition, surface volatile loss may produce a thin, dust-rich, lag deposit without appreciable strength [6, 9] that inhibits relaxation of topography with wavelengths comparable to or less than the thickness of this layer. If craters form on comets, their initial morphologies should correspond to those familiar from terrestrial impacts or from other planetary contexts [8], but with viscous relaxation in JFCs, their present morphologies would be modified depending on the detailed thermal history as well as composition and material properties.

References: [1] A'Hearn M. (2005) in *Comets II*, M. Festou et al. (eds.), Univ. of Ariz. Press, Tucson, 17-22. [2] Morbidelli A. and Brown M. (2005) in *Comets II*, M. Festou et al. (eds.), Univ. of Ariz. Press, Tucson, 175-191. [3] Rickman H. (2005) in *Comets II*, M. Festou et al. (eds.), Univ. of Ariz. Press, Tucson, 205-208. [4] Soderblom L. et al. (2004) *Icarus, 167*, 4-15. [5] Brownlee D. et al. (2004) *Science, 304*, 1764-1769. [6] A'Hearn M. F. et al. (2005) *Science, 310*, 258-264. [7] Giblin I. et al. (1994) *Icarus, 110*, 203-224. [8] Melosh H. J. (1989) *Impact Cratering: A Geologic Process*, Oxford Univ. Press, New York. [9] Prialnik D. et al. (2005) in *Comets II*, M. Festou et al. (eds.), Univ. of Ariz. Press, Tucson, 359-387. [10] Durham W. B. et al. (1997) *JGR, 102*, 16,293-16,302. [11] Goldsby D. L. and Kohlstedt D. L. (2001) *JGR, 106*, 11,017-11,030. [12] Weissman P. R. et al. (2005) in *Comets II*, M. Festou et al. (eds.), Univ. of Ariz. Press, Tucson, 337-357.

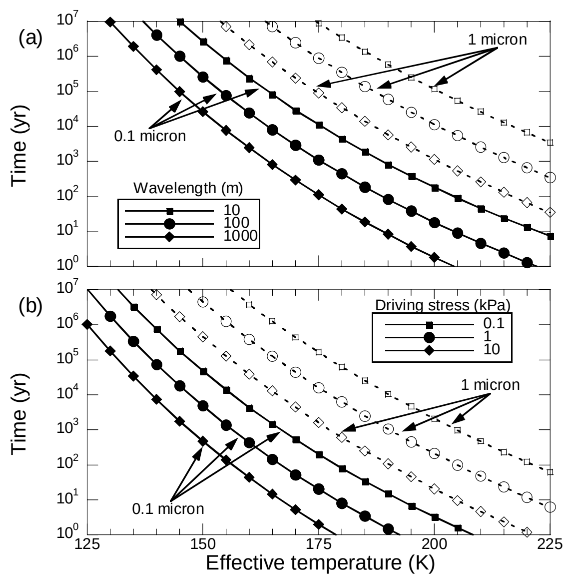

Figure 1. Relaxation timescales as a function of effective comet temperature, for two ice grain sizes: 0.1 μm (solid lines, filled symbols) and 1 μm (dashed lines, open symbols). (a) Timescales for topographic relaxation, for three values of wavelength. (b) Timescale for elongated comet to become more spherical, for three values of driving stress.