HIGH SILICATE CRYSTALLINE-TO-AMORPHOUS RATIOS IN COMETS C/2001 Q4 (NEAT) AND HALE-BOPP.
D. H. Wooden[1], D. E. Harker[2], and C. E. Wodward[3], [1]NASA Ames Research Center, MS 245-3, Moffett Field, CA 94035-1000, wooden@delphinus.arc.nasa.gov, [2]CASS/UCSD, 9600 Gilman Dr. Dept. 0424, La Jolla, CA 92093-0424, harker@talos.ucsd.edu, [2]Dept. of Astronomy, 116 Church St., SE, Univ. of Minnesota, Minneapolis, MN 55455, chelsea@astro.umn.edu.

Introduction: Crystalline silicates, by their apparent absence in the ISM [1], are dust grains that experienced high temperatures in the solar nebula. Mg-rich crystalline silicates formed either by condensation [2] from hot nebular gases (1450 K) or by the annealing [3, 4] of Mg-rich amorphous silicates (~1000 K) in shocks in the 5—10AU region [5] or by radial transport into and out of the hot inner zones, e.g., T_d>1000K at r_h<5AU, 10^{-6} –10^{-5} M_O yr^{-1}, $\alpha=10^{-4}$ [6] of the early solar nebula [7]. Mg-rich crystalline silicates are found in interplanetary dust particles (IDPs) [8] and produce IR spectral features in many Oort cloud comets [9,10,11]. In May 2004, we discovered strong crystalline silicate features in the dynamically new Oort cloud comet C/2001 Q4 (NEAT). Thermal emission modeling of comets Q4 and C/1995 O1 (Hale-Bopp) demonstrate that both these comets have similar, high silicate crystalline-to-amorphous ratios of 2.4 [12] and 2.1 [13], respectively, indicating that these icy planetesimals aggregated from similar reservoirs of material or that crystalline silicates were widely distributed within the comet-forming zone. This argues for efficient annealing mechanisms and radial mixing [14].

Cometary Silicate Crystalline-to-Amorphous Ratios: Primitive grains released from cometary muclei into their comae during perihelion passage reveal the conditions in the solar nebula during the regime of icy planetesimal formation. The relative abundance of silicate crystals to amorphous silicates deduced for cometary comae can be used to constrain high-temperature processes in protoplanetary disks, as the silicate crystalline-to-amorphous ratio probes the combination of the relative masses of grains that reached temperatures above 1000 K versus those that did not and the degree of radial mixing of the high-temperature processed materials with cooler materials.

Constraining the relative abundances of mineral grains from IR spectra of comets requires fitting thermal emission models to cometary spectral energy distributions (SEDs). Computing thermal emission models requires solving for the radiative equilibrium temperatures of discrete mineral grains characterized by a radius a and whose relative number are defined by a size distribution $n(a)$. Size distributions are either power-law or modified power law such as the Hanner size distribution $n(a) = (1-a_o/a)^m\ (a_o/a_p)^n$ where a_o=0.1μm and a_p is the grain radius at which the size distribution peaks. The radiative equilibrium temperatures of grains of a given radius of different mineral composition will differ because of their absorptivity or emissivity at visible to near-IR wavelengths and mid- to far-IR wavelengths. Specifically, at the same heliocentric distance, Mg-rich crystalline silicates are cooler than Fe-bearing amorphous silicates because Mg-rich crystals absorb sunlight significantly less efficiently than Fe-bearing amorphous silicates. The temperatures, and hence the optical properties, of Fe-bearing amorphous silicates are confirmed by fitting the relative fluxes of the 10 and 20μm features in the cometary SEDs [10]. The detection of Mg-rich crystalline silicates is confirmed by the wavelengths of their resonant peaks [9, 11, 15, 16] and their optical properties are confirmed by fitting thermal emission models to the ISO SWS spectrum of comet Hale-Bopp at 2.8 AU [10].

In order for any silicate feature to be detected in a comet's SED, there must be a preponderance of submicron silicate grains in the coma. Grain aggregates with submicron grain constituents may show features if porous enough [10, 17, 18]. Solid (non-porous) grains larger than ~1μm produce weak emission within the spectral resonance wavelength range in contrast to emission at wavelengths outside their resonances. For the sharp resonant peaks of Mg-rich silicate crystals to be detected in contrast to the strong broad spectral resonances of amorphous silicates, the crystals must be as or more abundant than the amorphous grains: their cooler temperatures mean they produce less flux and their relative numbers need to be greater in order to be detected in constrast to the warmer amorphous silicates.

Comets Q4 and Hale-Bopp had silicate features with remarkably similar shapes as shown in Fig. 1. Fitting thermal emission models to comet Q4 [12] and Hale-Bopp [13] constrains their relative mineral abundances. The silicate crystalline-to-amorphous ratios derived for comets Q4 and Hale-Bopp are 2.4 and 2.1 respectively.

Constraints on High Temperature Processes in the Solar Nebula Provided by Comets Hale-Bopp and Q4 : Hale-Bopp was observed to have the largest contrast silicate feature to date and is deduced to have a grain size distribution that peaks at 0.2μm [10]. The structure of Hale-Bopp's coma was also dominated by jet activity. We hypothesize that small pristine grains, grains minimally altered since their formation and aggregation as grains and their incorporation into the nucleus, were dredged up from the subsurface layers of the nucleus and expelled into the coma via jets and/or that pristine grains fragmented in the coma [10,12]. Comet Q4 has a parabolic orbit and also has strong jet activity close to perihelion [19]. Comet Q4 has not suffered the nuclear surface processing that occurs through repeated perihelion passages [20] that leads to the loss of volatiles from the near-surface layers of the nucleus and potentially decreases the fragility of grain aggregates and decreases the silicate-to-amorphous carbon ratio though the carbonization [21,22] of the organic "glue" [23] that holds grain aggregates together. Probably both comets Q4 and Hale-Bopp are releasing primitive grains into their comae through their strong jet activity. Thus, their high silicate crystalline-to-amorphous ratios provide strong constraints on high temperature processes in the early solar nebula and on the radial mixing of grains processed at high temperatures (>1000K) into the Jupiter–Saturn region [24] and to some extent into the trans-Neptunian region [25]. A silicate crystalline-to-amorphous ratio of 0.5 is predicted by radial diffusion models of the early solar nebula, given a warm nebula model and rapid (300,000 yr) radial diffusion of annealed silicate grains from the hot inner regions to throughout the disk [7]. The high silicate-to-amorphous ratios deduced for comets Q4 and Hale-Bopp of 2.4 and 2.1 indicate efficient annealing mechanisms such as heating in shocks [5] and efficient radial mixing [14].

References:

[1] Kemper F. et al. (2004) ApJ, 609, 826. [2] Grossman L. (1972) GCA, 36, 597. [3] Rietmeijer F. J. M. et al. (2002) Icarus, 156, 269. [4] Brucato J. R. et al. (1999) A&A, 348, 1012. [5] Harker D. E. and Desch S. P. (2002) ApJ, 565, L109. [6] Bell K. R. et al. (2000) in Protostars and Planets IV, ed. V. Mannings et al. (Tucson: Univ. Arizona Press), 897. [7] Bockelee-Morvan D. et al. (2002) A&A, 384, 1107. [8] Bradley, J. P. et al. (1999) in In Solid Interstellar Matter: The ISO Revolution, ed. L. d'Hendecourt et al. (Les Ullis: EDP Sciences), 297. [9] Wooden, D. H. (2002) EMP, 89, 247. [10] Harker D. E. et al. (2002) ApJ, 580, 579. [11] Wooden, D. H. et al. (1999) ApJ, 517, 1034. [12] Wooden D. H. et al. (2004) ApJ, 612, L77.[13] Harker D. E. et al. (2004) ApJ, 615, in press. [14] Boss A. P. (2004) ApJ, in press. [15] Crovisier J. et al. (1997) Science, 275, 1904. [16] Hanner M. S. et al. (1994) ApJ, 425, 274. [17] Bradley J. P. et al. (1999) Science, 285, 1716. [18] Xing Z. and Hanner M. S. (1997) A&A, 324, 805. [19] Lecacheux J. and Frappa E. (2004) IAU Circ. No. 8349. [20] Meech K. J. and Svoren J. (2004) in Comets II, ed. M. C. Festou (Tucson: Univ. Ariz. Press), in press. [21] Moroz L. V. et al. (2004) Icarus, 170, 214. [22] Moroz L. V. et al (2004) Icarus, submitted. [23] Boehnhardt H. et al. (1990) A&A, 231, 543. [24] Fernandez J. A. and Ip. W.-H. (1981) Icarus, 47, 470. [25] Morbidelli A. and Levison H. F. (2003) Nature, 422, 30.

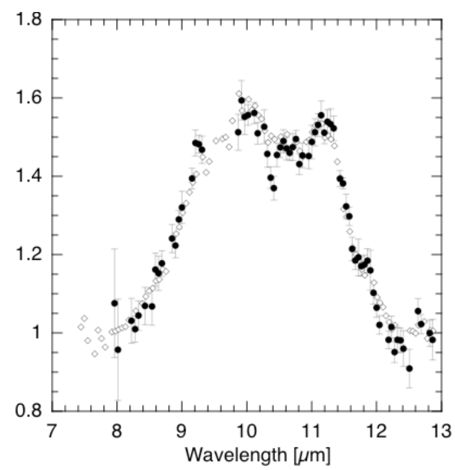

Figure 1: The silicate feature strength (flux-to-continuum ratio) derived from two HIFOGS spectra of comet C/2001 Q4 (NEAT) on 2004 May 11.30 UT (*solid circles*) [12] compared with the scaled (0.3) silicate feature derived from the HIFOGS spectrum of comet C/1995 O1 (Hale-Bopp) on 1997 February 15 UT (*open diamonds*) [11]. The flux-to-continuum ratios for Q4 (NEAT) are derived by dividing the HIFOGS flux spectra by a blackbody fitted to $\lambda \leq 8.4\mu m$ and $\lambda \geq 12.4\mu m$ and characterized by T_{bb}=310±4 K and F_λ=1.19±0.01E-16 W cm^{-2} μm^{-1}.