COMET DUST DIVERSITY IN GROUND-BASED AND SPITZER SPACE TELESCOPE MID-INFRARED SPECTRA.

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Introduction: The solar system's primitive bodies provide us with samples of the building blocks of our solar system, and help us ascertain the processes that were relevant in the evolution of our sun's protostellar disk. Specifically, the study of comets is beneficial to our understanding of dust formation and processing in the early solar nebula. Comet nuclei are the end results of the mixing of high temperature condensates from the inner-protosolar disk with ices, organics, and less processed dust in the outer-disk. Evidence for this mixing is provided by the observed crystalline silicate fractions (> 0.3) of comets (e.g., C/1995 O1 (Hale-Bopp)[1, 2], 9P/Tempel[3, 4, 5], 78P/Gehrels[6]), which are larger than the low crystalline silicate fraction (< 0.05) of the interstellar medium [7, 8, 9]. High temperature condensates did not form in the cold comet formation zone (heliocentric distances, r_h, $5 - 40$ AU), but were transported there, perhaps through large scale radial (meridional) flows [10, 11, 12]. The mineralogy of that newly formed dust depends on the environment in which it formed. For example, the Fe-to-Mg ratio of crystalline silicates in comets is sensitive to the amount of oxygen available at the time of formation: Fe-enriched silicate crystals may condense when the oxygen fugacity is high, but otherwise Mg-rich crystals are favored[13].

Mid-infrared (mid-IR) spectra and thermal emission models of comet dust comae are diagnostic of important dust grain properties: composition, size, and structure. We examine the composition of comet dust from mid-IR spectra to assess the efficiency of mixing of dust and planetesimals in the comet formation zone.

Observations: Over the course of *Spitzer*'s cryogenic mission, we obtained spectra of 54 comets, approximately half of which have a wavelength coverage and signal-to-noise ratio suitable for a detailed analysis with thermal models. In addition to the *Spitzer* spectra, we also observed comet C/2004 Q2 (Machholz) on 27 January 2005 and comet 8P/Tuttle on 17 January 2008 at the NASA IRTF with the MIRSI instrument [14]. A sample of our spectra is presented in Fig. 1.

Silicate diversity: Both the size and shape of the 8–12 μm silicate emission feature vary between comets in our survey. This suggests that comets have a range of silicate content. We will present thermal emission models to assess the validity of this conclusion. The variation in silicate features does not depend on dynamical class. Ecliptic comets, derived from the Kuiper Belt, typically have low silicate emission (10–30% over the continuum), and may or may not exhibit narrow resonance features due to the presence of crystalline silicates. Similarly, Oort cloud comets can also have weak silicate emission with or without the presence of silicate crystals.

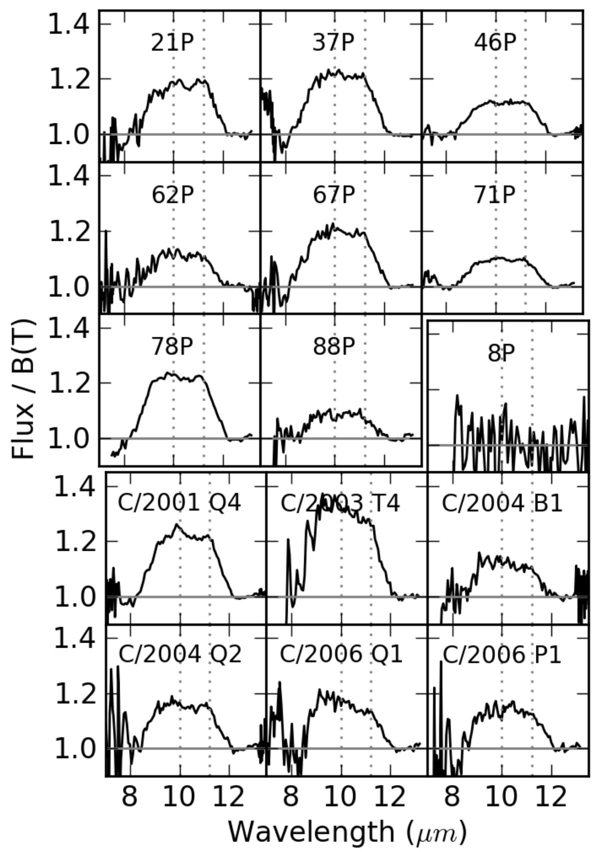

Figure 1: Spectra, normalized by a scaled Planck function, of 15 comets selected to show the diversity of silicate emission features observed in our survey. The upper 8 plots are ecliptic comets, the lower 7 plots are Oort cloud or Halley-type comets. Horizontal dotted-lines at 10.0 and 11.2 μm mark the nominal wavelengths of emission peaks from Mg-rich crystalline olivine (forsterite). Crystalline silicates are apparent in the spectra of 21P, 71P, 78P, C/2001 Q4, and C/2004 Q2.

Crystalline silicate mineralogy: The positions and relative strengths of emission peaks from crystalline silicates are diagnostic of their mineralogy [15, 16]. Specifi-

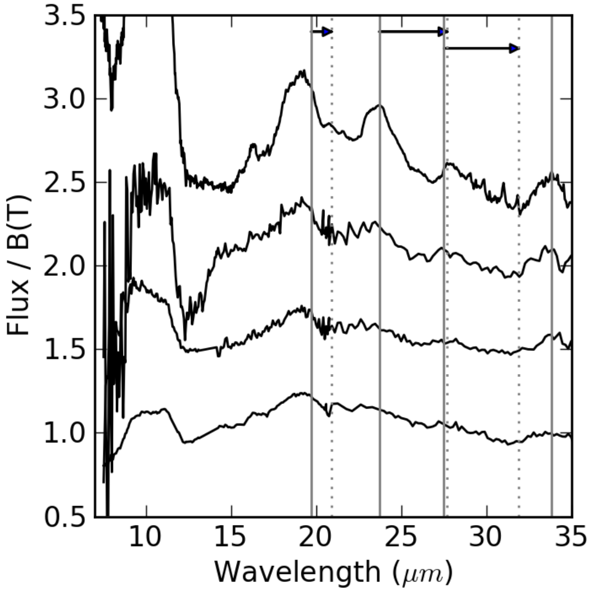

Figure 2: Spectra, normalized by a scaled Planck function, of 4 comets with 15–35 μm emission peaks due to crystalline olivine. Comets (bottom-to-top) 78P and C/2003 T4 were observed as part of our *Spitzer* survey, comet 29P is a *Spitzer* observation from [17], and comet Hale-Bopp was observed by [18] with *ISO*. Horizontal solid lines mark the nominal wavelengths for emission peaks from Mg-rich crystalline olivine (forsterite), and dotted lines mark the nominal wavelengths of Fe-rich olivine (fayalite) [16]. Arrows indicate how the olivine peaks change wavelength positions with increasing Fe content, except for the 34 μm peak, which moves off the plot and becomes very weak. The positions of peaks are coincident with the Mg-rich mineral, but detailed thermal emission modeling is required to formally assess this conclusion.

cally, the strong resonances from crystalline olivine at 15–35 μm observed in several comets can be used to estimate the Fe-to-Mg ratio. In Fig. 2, we present the 15-35 μm spectra of comets 78P/Gehrels and C/2003 T4 (LINEAR), along with comets 29P/Schwassmann-Wachmann (observed by [17]) and Hale-Bopp (observed by [18]). The positions of the olivine peaks all coincide with a Mg-rich mineralogy. One possible interpretation is that the bulk of the comet dust that formed in the solar nebula condensed from a low oxygen environment, where the Fe was reduced rather than oxidized and incorporated into silicates.

Discussion: The diversity of comet spectra may be explained by primordial or evolutionary processes. For example, the Kuiper Belt and Oort cloud could be comprised of comets that formed over a broad range of overlapping heliocentric distances, thus some ecliptic comets are compositionally the same as Oort cloud comets. This mixing may have occurred as a result of giant planet migration[19]. In a similar argument, the compositional similarities may arise from temporally varying dust compositions during the accretion of planetesimals (e.g., a high crystalline zone that started at 5 AU and moved out to 30 AU). On the other hand, evolutionary processes (e.g., irradiation, or de-volatilization) may similarly affect both dynamical classes.

References

[1] Harker, D. E., Wooden, D. H., Woodward, C. E., & Lisse, C. M. 2002, *ApJ*, 580, 579
[2] Harker, D. E., Wooden, D. H., Woodward, C. E., & Lisse, C. M. 2004, *ApJ*, 615, 1081
[3] Harker, D. E., Woodward, C. E., & Wooden, D. H. 2005, *Science*, 310, 278
[4] Lisse, C. M., et al. 2006, *Science*, 313, 635
[5] Harker, D. E., Woodward, C. E., Wooden, D. H., Fisher, R. S., & Trujillo, C. A. 2007, *Icarus*, 190, 432
[6] Watanabe, J., et al. 2005. *IAU Sym. Abs.* 229, 121
[7] Li, A., & Draine, B. T. 2001, *ApJ*, 554, 778
[8] Kemper, F., Vriend, W. J., & Tielens, A. G. G. M. 2004, *ApJ*, 609, 826
[9] Kemper, F., Vriend, W. J., & Tielens, A. G. G. M. 2005, *ApJ*, 633, 534
[10] Keller, C., & Gail, H.-P. 2004, *A&A*, 415, 1177
[11] Ciesla, F. J. 2007, Science, 318, 613
[12] Wehrstedt, M., & Gail, H.-P. 2008. *A&A*, submitted (astro-ph/0804.3377)
[13] Wooden, D. H. 2008, *Space Sci. Rev.*, 138, 75
[14] Deutsch, L., Hora, J., Adams, J., & Kassis, M. 2002, in Astronomical Telescopes and Instrumentation, *SPIE* 4841, 106
[15] Chihara, H., Koike, C., & Tsuchiyama, A. 2001, *PASJ*, 53, 243
[16] Koike, C., et al. 2003, *A&A*, 399, 1101
[17] Stansberry, J. A., et al. 2004, *ApJS*, 154, 463
[18] Crovisier, J. et al. 1997, *Science*, 275, 1904
[19] Levison, H. F., & Morbidelli, A. 2003, *Nature*, 426, 419

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