Silica Debris Star Systems – *Spitzer* Evidence for Lunar Formation Events & Crustal Stripping or Magma Oceans & Late Heavy Bombardments?

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Introduction. There is abundant inferential evidence for massive collisions in the early solar system [1]: Mercury's high density; Venus' retrograde spin; Earth's Moon; Mars' North/South hemispherical cratering anisotropy; Vesta's igneous origin [2]; brecciation in meteorites [3]; and Uranus' spin axis located near the plane of the ecliptic. By observing nearby young stars in the throes of solar system formation, we can study processes that formed our own solar system but have been obscured by waethering and evolutionary processes. Recent work [4] analyzing *Spitzer* mid-IR spectra has demonstrated the presence of large amounts of amorphous silica and SiO gas produced by a recent (within 10^3 – 10^4 yrs) large ($M_{Excess} > M_{Pluto}$) hypervelocity impact collision around the young (~12 Myr old) nearby star HD172555, at the right age to form rocky planets. Many questions still remain concerning the location, lifetime, and source of the detected silica/SiO gas, which should not be stable in orbit at the estimated 5.8 AU from the HD172555 A5V primary for more than a few decades. Here we discuss these questions, using inferences gleaned from the HD172555 and 3 new systems identified to have silica excesses (Fig. 1).

Instability of the Fine Silica Dust & SiO Gas in HD172555. Fine, 0.1 – 5 μm dust produced at 5.8 AU from an A5 star should be blown out by radiation pressure on timescales of a few decades. There are good arguments as well for brief lifetimes for SiO gas created by rock vaporization – a short UV photolysis lifetime (10^6 – 10^7 s, although self-shielding in dense systems and heterogenous grain catalysis could protect and reform it rapidly). SiO gas may also be blown on hyperbolic orbits by radiation pressure. Given the 3 other silica systems now identified, it is highly unlikely that we are fortuitously observing these systems immediately after silica formation - there must be instead an ongoing source of silica dust and SiO gas.

Lack of Fe/Mg in the HD172555 material. As shown in [4], a tabulation of the amount counts in the fine silica dust is decidedly Fe and Mg-atom poor compared to solar. Adding in the mass of SiO gas only makes the matter much worse, as there is roughly 10-100x more mass of gas than fine dust. Either the silica formation process creates SiO rich, Fe/Mg poor material, or it is released by this process from an already silica rich body.

Possible Sources & Locations for the Silica and SiO gas in HD17255. Given the questions of source, stability, and Fe/Mg extraction, and the large mass scale of the dust and gas excess, 3 possible system structures appear possible :

(1) A single hyperevelocity impact (>10km/s in order to produce silica and vaporize SiO at impact) creating an optically thick circumplanetary debris ring which is overflowing or releasing silica-rich material from its Hill sphere. Like terrestrial tektites, the Fe/Mg poor amorphous silica rubble is formed from quick-quenched molten/vaporized rock created during the impact. The amount of dust detected in the HD172555 system is easily enough to fill and overflow the Hill sphere radius of 0.03 AU for a Pluto-sized body at 5.8 AU from an A5 star, unless it is optically thick (> 1 cm in physical depth). Such a disk would provide a substantial fraction of the observed IR flux, and will be dense enough to self-shield its SiO gas, greatly extending its photolytic lifetime. The lifetime for such a system versus re-condensation into a solid body like the Moon is short, though, ~ 10^3 to 10^4 yrs [5]. Credence is lent to this scenario by observations of the Jovian impact in July 2009 [6], where absorption features due to silica have been found superimposed on those of hot ammonia at the > 60 km/s impact site (Fig. 1).

(2) Ongoing multiple small hypervelocity impacts continuously grinding down a distribution of large circumstellar particles above the blowout size limit (the "rubble" identified in [4]) and releasing silica rich material and SiO gas. This model would require a massive (>1 M_{Moon}) belt of 10um – 1 cm particles with inclinations spread out over at least ±45° [4] or dust on highly eccentric orbits [7]. The amount of material implied by the relative amplitude of the rubble spectral feature is consistent with the amount needed to collisionally produce the fine silica dust [4, 8]. A body rapidly reaccreting in a debris ring after collisional disruption (like the Moon) would have similar behavior (lots of impacts for some time, producing gas and little melt droplets) [9].

(3) A single impact onto a silica-rich object with already highly differentiated surface layers. For a very young system at 10-20 Myr when we expect planets to be rapidly accreting, a Mercury or larger-sized rocky body covered in an SiO rich magma ocean is very likely by the Jeans energy criterion [9], even without considering additional heating input by ^{26}Al and other radioactives. For the lowest expected impact velocities, $v_{\text{Mercury Escape}}$ = 4 km/s, a pre-existing magma ocean in equilibrium with a surrounding SiO atmosphere would be required; at higher velocities the impacting body could be the formative mechanism for the magma ocean [10].

Other Non-Primordial Silica Rich Star Systems. In this abstract we also update the record to include 3 more nearby F-star systems which have excess circumstellar emission due to silica dust, out of ~1000 examined, for a $\text{Probability}_{\text{detection}} \leq 1\%$ and a length of the silica-rich phase $\leq .01 * 10^7$ yrs = 10^5 yrs. With 4 systems now detected, we can rule out the possibility of fortuitously observing the silica immediately after a giant impact. The youngest of these, HD154263, at ~20 Myr age shows evidence for SiO gas and amorphous + crystalline silica. The 2 older systems, HD23514 at ~100Myr age, and HD15407 at ~2 Gyr, conspicuously do not show any evidence for SiO gas while exhibiting strong features mainly due to crystalline silica (Fig. 1). HD23514 also shows evidence for large amounts of amorphous carbon, PAHs, and nanodiamonds, due to a strongly enhanced C-atom abundance in impactor or impactee. HD15407, the oldest system, also does not show any conclusive evidence for the presence of large dark particles (“rubble”).

Silica Evolution in the Mature Systems. While we have only the 4 systems to argue from, there does appear to be a clear trend of decreasing SiO gas content with system age, arguing that any SiO gas created is relatively transient, disappearing on timescales of < 1 Myr, possibly recombining to form crystalline silica species. As the oldest system at 2 Gyr also shows a paucity of large particle rubble, we infer that this rubble is cleared on timescales < 1 Gyr.

The *Spitzer* spectrum of HD145263, like that of HD17255, can be explained by any one of the 3 model scenarios listed above, consistent with current rocky planet formation theories on timescales of ~10Myr when oligarchic growth is expected. From the instability arguments given above, the SiO gas must be located in a circumplanetary torus; the fine silica dust is continuously created by collisional grinding of the large rubble particles, either in the re-coalescing circumplanetary torus or in circumstellar orbit.

The *Spitzer* spectra of the older HD23514 and HD15407 can be formed by the 3 mechanisms listed, but one other scenario becomes possible with the 0.1 – 2 Gyr ages for these systems: differentiation and alteration processes on silica-rich, mature terrestrial planets (e.g., the action of plate tectonics/subduction /volcanism coupled with atmospheric CO_2 and free liquid H_2O creating abundant crustal quartz on a Gyr timescale). The massive late impact could be provided by the equivalent of these systems’ Late Heavy Bombardment (occurring at 0.7 ± 0.1 Gyr in the solar system) [11,12]. Future work will explore this possibility more fully.

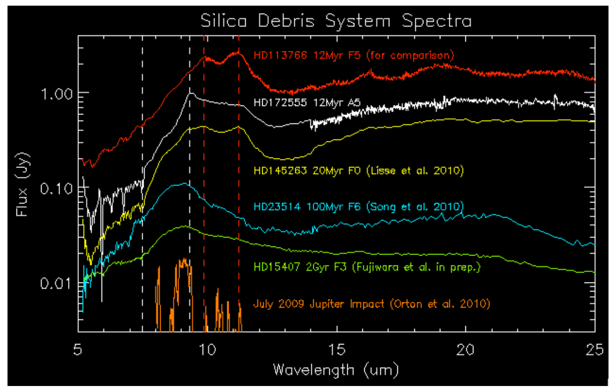

Figure 1 - Comparison of the mid-IR spectra of 4 silica dominated systems with the “normal” olivine and pyroxene dominated spectrum of HD113766 [13] and the excess absorption spectrum of the July 2009 Jovian impact [6]. The dashed white lines denote the empirical positions of the SiO fundamental absorption edge (~7.5 um) and the amorphous silica peak (~9.2 um). The dashed red lines denote the typical 9.8 and 11.2 um silicate peaks.

References:

[1] Hartmann, W.K., and Vail. S.M., 1986. “Giant Impactors - Plausible Sizes and Populations”, in *Origin of the Moon*, Proc. of the Conference, Kona, HI, Oct 13-16, 1984 (A86-46974 22-91). Hartmann, Phillips, and Taylor (eds). Houston, TX, LPI 551 **[2]** Drake, M.J. 2001, *MAPS* **36**, 501 **[3]** Bischoff, A. *et al.*, 2006. In *Meteorites and the Early Solar System II*, Lauretta and McSween (eds.), U of Arizona Press, Tucson, 943 pp., p.679-712 **[4]** Lisse, C.M., *et al.*, 2009. *ApJ* **701**, 2019 – 2032 **[5]** Pahlevan, K., and Stevenson, D.J., 2007, *Earth and Planetary Science Letters* **262**, 438 **[6]** Orton, G. *et al.* 2010 (in preparation) **[7]** Wyatt, M.C. *et al.* 2009 arXiv:0910.4725 (*MNRAS* in press) **[8]** Thebault & Augereau, 2007, *Astron. Astroph.* **472**, 169 **[9]** Fegley, B. & Shafer, L. 2005. *Bulletin of the American Astronomical Society*, **37**, p.683 **[10]** Aspaugh, E. *et al.* 2005, LPSC 36, Abstract No. 2393 **[11]** Wyatt M. C., *et al,* 2007, *ApJ* **658**, 569 **[12]** Svetsov, V.V. 2005, *Planetary and Space Science* **53**, 1205 **[13]** Lisse, C.M. *et al.* 2008, *ApJ* **673**, 1106