Spitzer Evidence for a Late Heavy Bombardment and the Formation of Urelites in η Corvi at ~1 Gyr.

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Introduction. We have analyzed the Spitzer IRS 5 – 35 um spectrum of the warm, ~360K circumstellar dust around the nearby MS star η Corvi (F2V, 1.4 ± 0.3 Gyr), a known IRAS excess object with a very high 24um excess luminosity for its age (Fig. 1). The Spitzer spectrum (Fig. 2) shows clear evidence for warm, water- and carbon-rich dust at ~ 3 AU from the central star, uncoupled and in a separate reservoir from the system's extended sub-mm dust ring at 150 ± 20 AU [2,3] (Figs. 1 & 3).

Spectral features similar in kind and amplitude to those found for ultra-primitive material in ISO HD100546 spectra were found (water ice & gas, olivines & pyroxenes, amorphous carbon and metal sulfides), in addition to emissions due to impact produced silica and high temperature/pressure carbonaceous phases [4]. A large amount, at least 3 x 10^{19} kg, of 0.1 – 1000 μm warm dust is present, in a roughly collisional equilibrium distribution with dn/da ~ $a^{-3.5}$. This is the equivalent of a 140 km radius asteroid of 2.5 g cm^{-3} density or a "comet" of 260 km radius and 0.40 g cm^{-3} density. If we allow for particles larger than 1 cm, the mass present increases by (largest particle size/1000 μm)$^{0.5}$, and the equivalent parent body radius increases by the 0.167th power.

Findings From Our Analysis [4] :

- The η Corvi system emits > 1000 times as much 24 um flux as other co-eval (~1 Gyr) dusty disk systems. It is within a factor of 2 of the age of the solar system during the LHB.

- The η Corvi system contains an extended belt of cold Kuiper Belt dust (Mass ~ 2 x 10^{23} kg = 3 M_{Moon}) at ~150 AU from the primary.

- The η Corvi system contains a reservoir of warm (~360K) dust massing ~10^{-4} the mass of the Kuiper Belt dust) at ~3 AU from the primary, in the system's Terrestrial Habitability Zone (THZ), spatially separated by more than 50 AU from the cold dust.

- The warm dust is ***very*** primitive, & definitely not from an asteroidal parent body. It is very water ice & carbon rich, and its spectrum matches best the emission seen from the cold, extended dust disk found around HD100546, an ~10 Myr old Herbig A0V.

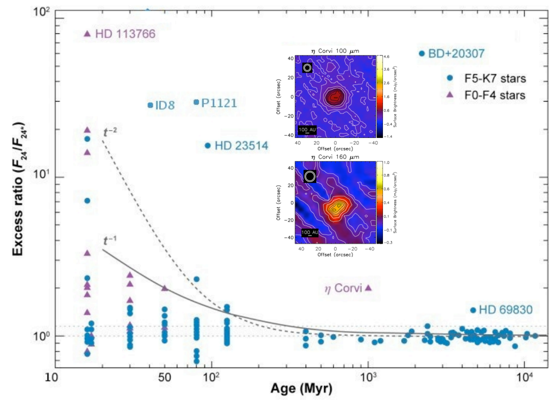

Figure 1 - Dusty disk IR excess luminosity vs time. η Corvi is the 3rd brightest of [1]'s 59 IRAS-excess systems, and the only one which is a "mature" MS system of ~1.4 Gyr age, or about 1/3 of its total MS lifetime. The 1/t and 1/t^2 trend lines fit most of the sources in the current sample except outliers like η Corvi, which clearly has a high $L_{IR}/L_* = 3 \times 10^{-4}$ for its age, suggesting something unusual has occurred in this system. *Inset*: 100 um (top) and 160 um (bottom) Herchel PACS FIR images of the extended bright η Corvi Kuper Belt, after [2]. Contours are shown at 0, 10, 30, 50, 60, 70, 80, 90 and 99% of the peak in the map. Circles in the upper left corner of each panel mark the nominal beam sizes.

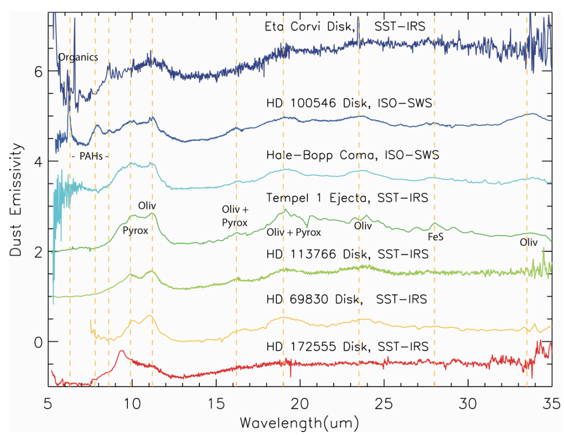

Figure 2 – Comparison of the mid-IR spectra of η Corvi with the spectra of dust from: a young, organic rich Herbig A0 star building a giant planet (HD100546) [5]; two comets (Hale-Bopp and Tempel 1) [5]; a young F5 star building a terrestrial planet (HD113766) [6]; the silica-rich debris created by a hypervelocity impact in the HD172555 system [7]; and a mature main sequence star with a densezodiacal cloud (HD69830) [8]. The similarity between the ~1 Gyr old η Corvi dust and the ~10Myr old HD100546 spectra is readily apparent.

- The warm dust mass is 10^4 – 10^7 larger than that of a solar system comet (10^{12} – 10^{15} kg), but is very similar to the mass of a large Centaur or medium sized Kuiper Belt object (10^{19} – 10^{21} kg).

- The warm THZ dust contains ~40% amorphous silica, not found in primitive solar system materials like comets and meteorites in such high abndance, arguing for an impact delivery of the material.

- The particle size distribution of the dust is $dn/da \sim a^{-3.5}$, with a deficit for particles ≤ 1 μm in size, as expected for dust created from collisional grinding of impact fragments over > 10^3 yrs.

- The *Spitzer* warm dust excess spectrum closely matches spectra reported for the Ureilite meteorites of the Sudan Almahata Sitta fall in 2008, suggesting, since the source of the η Corvi warm dust is its excited Kuiper Belt, that the Ureilite parent body was formed in our solar system by an impact between a KBO and an S-type asteroid.

- The amount of water tied up in the observed circumstellar material, ~10^{18} kg, is > 0.1% of the water in the Earth's oceans, & the amount of carbon present is also considerable, ~10^{18} kg. The total amount of warm dust mass is similar to the 10^{19} – 10^{20} kg estimated to have been delivered to the Earth-Moon system during the solar system's LHB.

Conclusions. The best model for what is going on in the η Corvi (F2V) system is that some process (*e.g.,* planetary migration) is dynamically exciting the Kuiper Belt, causing frequent collisions amongst KBOs and producing the observed copious Kuiper Belt dust. As part of this process, one or more of the excited KBOs was scattered onto an orbit that sent it into the inner system, where it collided with a planetary-class body at ~3 AU, releasing a large amount of thermally unprocessed, primitive ice and carbon-rich dust.

The parent body for the observed warm dust was thus a Kuiper-Belt or Centaur-like body, which captured a large amount of early primitive stellar nebula material and kept it in deep freeze for ~1 Gyr, and was then prompted by dynamical stirring of its parent Kuiper Belt into colliding with a rocky body at ~3 AU at moderate velocities (5-10 km sec^{-1}). The impact velocity was slow enough to preserve most of the original refractory silicates but also fast enough to refreeze ~1/3 of it as silica material, while also delivering large amounts of water (~1% of the mass of Earth's Oceans) and carbon rich material to the planetary body.

While this system is likely a good analogue for the LHB processes that occurred in the early Solar System at 0.6 – 0.8 Gyr after the formation of the CAIs, many things are still not clear: the number of bodies impacting the inner system; the timing and duration of the impacts; the nature of the rocky impactee; or the role the system's planets play in causing the impacts. **η Corvi is thus worthy of further detailed study in order to understand the nature of our LHB**, and to perform a search for a rocky planetary body at ~3 AU (the impactee), and for a giant planet at ~115 AU (the KB dynamical stirrer at ~ the 3:2 resonance of the KB dust at 150 AU).

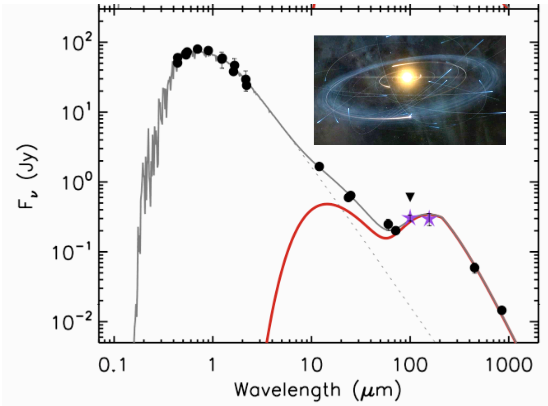

Figure 3. SED for η Corvi showing the 0.4 – 2.2 μm BVR/2MASS system photometry dominated by stellar photospheric emission, the stellar/circumstellar dust MIR flux measurements of IRAS and Spitzer, & the cold FIR excess measured by Herschel and JCMT/SCUBA [2]. Solid grey line: combined fit to the η Corvi SED using a 2-blackbody model (red) with warm (350K) & cold (35K) dust reservoirs + emission from a Kurucz F2V photosphere (dashed line) [4].

References: [**1**] Chen, C. H., *et al.* 2006, *ApJS* **166**, 351; [**2**] Matthews, B.C., *et al.* 2010. *Astron. & Astrophys.* **518**, L135 [**3**] Wyatt, M.C. *et al.* 2005. *Astrophys. J.* **620**, 492; **[4]** Lisse, C.M., *et al.*, 2011. *ApJ* (in press; published on-line as 2011arXiv1110.4172L)**; [5]** Lisse, C.M. *et al.*, 2007, *Icarus* **187**, 69; [**6**] Lisse, C.M. *et al.*, 2008, *ApJ* **673**, 1106 [**7**] Lisse, C.M. *et al.*, 2009, *ApJ* **701**, 2019; [**8**] Lisse, C.M., *et al.* 2007, *ApJ* **658**, 584

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