Origins: from the Protosun to the First Steps of Life
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Outbursts of young Sun-like stars may change how terrestrial planets form

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Abstract. While the Sun is nowadays a quiet and well-balanced star, in its first few million years it might have been often out of temper, like those young low-mass stars which episodically undergo unpredictable outbursts. The prototype of one of the two classes of young erupting stars, EX Lupi, had its historically largest outburst in 2008. It brightened by a factor of 30 for six months, due to elevated accretion from the circumstellar disk on to the star. Our group observed the system during the outburst, and discovered the crystallisation of amorphous silicate grains in the inner disk by the heat of the outburst. Our mid-infrared monitoring of the freshly produced crystals revealed that their emission in the inner disk quickly dropped already within a year after the outburst. Here we report on new observations of the 10 μm silicate feature, obtained with the MIDI and VISIR instruments at Paranal Observatory, which demonstrate that within five years practically all forsterite disappeared from the inner disk. We attempt to model this process by an expanding wind that transports the crystals from the terrestrial zone to outer disk regions where comets are supposed to form. Since the eruptions of EX Lup are recurrent, we speculate that the early Sun also experienced similar brightenings, and the forming planetary system might have incorporated some of the mineralogical and chemical yields provided by the outbursts. EX Lup, as a proxy for the proto-Sun, may be a telltale object to understand the origin of molecules and minerals we routinely encounter on Earth.

Keywords. stars: pre-main sequence, circumstellar matter, individual(EX Lup)

1. Eruptive phenomena during early stellar evolution

Over a period of 10^5–10^6 yrs, the material of the circumstellar disks around low-mass pre-main sequence stars is, to a large part, being accreted onto the protostar, building up its final mass. This process, however, is far from being smooth. In addition to the usual daily-weekly fluctuation of the accretion rate observed in T Tauri stars, there are episodic events of enormously increased accretion rate, which lead to temporary brightenings of the system. Young eruptive objects are traditionally categorized into two classes. EX Lupi-type stars (EXors) are defined by their repetitive outbursts lasting several months, while FU Orionis-type objects (FUors) produce decade-long and more energetic outbursts (Hartmann & Kenyon 1996, Audard et al. 2014). The optical brightness change is 3–5 mag, corresponding to a 10–100 times increase of the accretion rate from the inner disk onto the star.

2. The 2008 outburst of EX Lup

In 2008 EX Lup, the prototype of the EXor class, underwent its historically largest outburst, brightening by about 5 magnitudes in visual light for a period of six months. Our group obtained a 5–37 μm spectrum with the InfraRed Spectrograph of the Spitzer

Space Telescope on 2008 April 21, shortly after the peak of the outburst. Comparing our spectrum with a pre-outburst observation from 2005, we detected new spectral signatures of crystalline silicate material, mainly forsterite, appeared during the outburst (Fig. 1).

We investigated several possible scenarios for the origin of these crystalline features. One possibility was that the crystalline particles were already present on the disk surface, but due to the higher luminosity during the outburst they became better illuminated and visible. Our calculations, however, demonstrated that the required change in luminosity is significantly higher than observed, thus this explanation was excluded. Another possibility was that crystalline material already existed in the midplane of the disk, and was transported to the disk surface by vertical mixing processes related to the increased turbulence during outburst. The calculated timescales for this process, however, turned out to be much longer than the length of the outburst. Therefore, our conclusion was that the originally amorphous silicate grains were transformed to crystalline grains in the inner disk via annealing, a process highly efficient above 1000 K. The appearance of crystalline forsterite grains in EX Lup was the first direct observation of on-going silicate crystallization in a celestial object (Ábrahám et al. 2009).

3. The disappearance of crystalline material

The outburst of EX Lup ended in 2008 September. In order to document any subsequent changes in the silicate features, we obtained post-outburst Spitzer spectra on 2008 October 10 and 2009 April 6 (Fig. 1). While we expected that the crystalline features in the 10 μm emission peak became relatively stronger after the inner disk surface had become fully crystallized, our observations showed that the degree of crystallinity in the 10 μm feature *decreased* with time, while strong peaks related to cold forsterite grains appeared in the 30 μm range. Juhász et al. (2012) performed radiative transfer and turbulent mixing calculations to disentangle the effects potentially responsible for decay of crystalline peaks around 10 μm. Their results excluded that vertical mixing could have replaced the freshly formed crystals by amorphous particles from the interior of the disk. Instead, the authors suggested the radial outward transportation of the silicate crystals by a wind driven by the outburst. The appearance of cold forsterite peaks in the 30 μm range supported this scenario.

Aiming to follow the further fate of the crystalline particles after the 2008 outburst and to understand the physical processes in action, we performed new N-band observations of EX Lup on 2016 August 20 using the VLT/VISIR instrument. Moreover, we analyzed archival mid-infrared interferometric observations obtained with the VLTI/MIDI instrument on 2013 May 27/28. Both mid-infrared spectra, plotted in Fig. 1, show similar results: the crystalline spectral features, detected in 2009, have completely disappeared from the 10 μm silicate peak, and the shape of the emission feature is identical with the pre-outburst one representative of amorphous dust grains. The inner disk returned to its original amorphous state just in 5 years.

4. Radiative transfer modelling

In order to test the outward transportation hypothesis of Juhász et al. (2012), we performed radiative transfer modeling of EX Lup in its pre-outburst and post-outburst states, using the RADMC3D code. We assumed that all crystalline grains were created during the outburst between 0.3 au and 0.7 au, and later they were driven outward by a disk wind. To model this, we added to the circumstellar disk component an expanding hollow crystal-rich sphere of constant width, and fitted the mass and radius of the sphere to the observed spectra. For details of the modeling process, see Ábrahám et al. (2019).

Our best-fit models are overplotted in Fig. 1 with red curves. In these models the shell

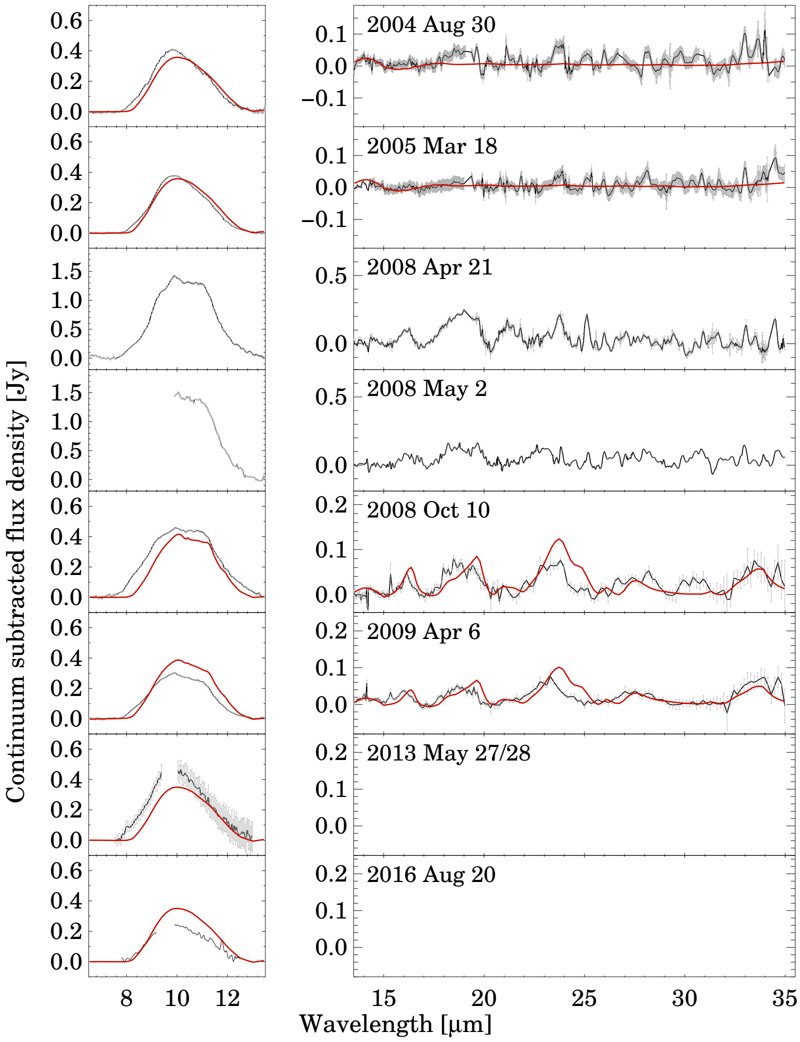

Figure 1. Continuum subtracted spectra of EX Lup at different epochs. Black curves are observations, red curves show our models.

transports $\sim 2\times 10^{23}$ g of forsterite, corresponding to about 10^4 Hale-Bopp-like comets. In order to match the shape of the 10 μm feature in 2008 October and 2009 April, we had to place the shell at r=1.2 au and 1.5 au, respectively. To be consistent with our spectra from 2013/2016, the sphere must be more distant from the star than 2.5 au.

5. Conclusions

With some assumptions, our modeling results can be used to constrain the likely location of the crystalline particles at any date (shaded area in Fig. 2). Comparing the data points for 2008 October and 2009 April, we can derive an average expansion velocity of $\sim$3 km/s, which is a rather low value for stellar winds, but fits into the wind velocity range found by Banzatti et al. (2018) in some cases in a sample of T Tauri stars. According to the figure, currently the forsterite grains are situated somewhere between 3.5 au and 7 au. This radial distance range overlaps with the expected location of the water snowline in the EX Lup disk ($\sim$5 au). Thus we may conclude that the crystalline grains

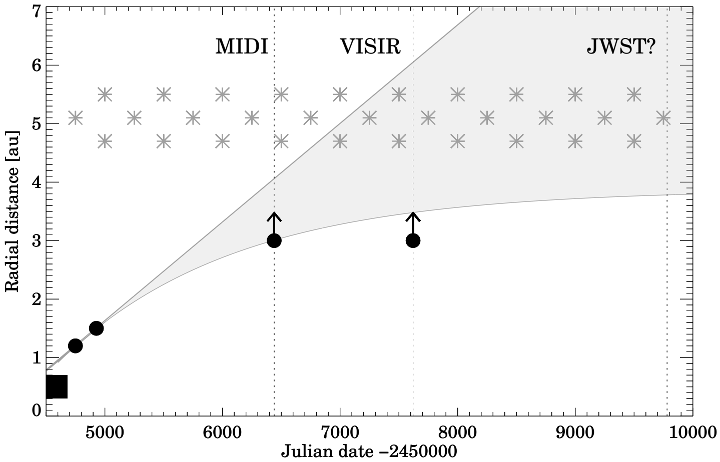

Figure 2. Radial location of the expanding sphere of crystal-rich dust as predicted by our modeling. The black square is the outburst in 2008, the two data points around JD∼4700 and 4900 are the Spitzer Space Telescope observations in 2008 October and 2009 April, while the lower limits are our MIDI and VISIR measurements. Asterisks mark the location of the water snowline. The shaded area is the probable location of the crystalline forsterite grains.

created in the 2008 outburst will likely reach and cross the water snowline. Since it is the formation zone of icy planetesimals, we speculate that the forsterite grains could be incorporated into cometary bodies, providing a possible explanation for the enigmatic high crystalline fraction in solar system comets, too.

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Discussion

Kamp: There is some degeneracy in the 10μm Si-feature concerning size and crystallinity. Did you consider the possibility of grain growth at all in building your scenario to explain the temporal changes seen in your 10μm Si Features?

Ábrahám: Indeed, both grain growth and crystallization changes the shape of the silicate feature, but in a somewhat different way. In the EX Lup spectrum obtained close to the peak of the outburst on 2008 April 21, we identified a relatively sharp peak at 10 μm, a well-defined shoulder around 11.3 μm, and a smaller peak at 16μm. All these features are characteristic of crystalline forsterite emission, thus in our case grain growth could be excluded as possible explanation for the observed changes in the spectral shape.