1 Supplementary Discussion

1.1 Spitzer observations and data reduction

We obtained spectra of EX Lupi with the Infrared Spectrograph (IRS)[27] on-board the Spitzer Space Telescope, on 2008 April 21. We used both the low-resolution modules ($R = 60 - 120$) in the 5.2–14.5 μm wavelength range, and the high-resolution modules ($R = 600$) between 9.9–37.2 μm. A high accuracy PCRS peak-up was executed prior to the spectroscopic observations to position the target within the slit. The integration time was set to six seconds for all modules, with four observing cycles for redundancy. For the low-resolution observations, the background was subtracted using associated pairs of imaged spectra from the two nod positions along the slit, also eliminating stray light contamination and anomalous dark currents. For the high resolution observations a separate background measurement was performed with the same set-up.

Pixels flagged by the data pipeline as being "bad" were replaced with a value interpolated from an 8 pixel perimeter surrounding the errant pixel. Our spectra are based on the `droopres` and `rsc` products processed through the S15.3.0 version of the Spitzer data pipeline for the low and high resolution data, respectively. The low resolution spectra were extracted using a 6.0 pixel fixed width aperture in the spatial dimension, while for the high resolution channels we extracted the spectra by fitting the source profile with the known psf in the spectral images. The low-level fringing in the high resolution spectra was removed using the `irsfinge` package[28]. The spectra are calibrated using a spectral response function derived from IRS spectra and MARCS stellar models for a suite of calibrators provided by the Spitzer Science Centre. To remove any effect of pointing offsets, we matched orders based on the point spread function of the IRS instrument, correcting for possible flux losses. A section of the spectrum centred on the forsterite peak at 16 μm is shown in Fig. 1.

A pre-outburst observation was obtained by Stringfellow et al. (PID: 3716) on 2005 March 18 which is now available in the Spitzer archive. The instrumental set-up was identical with our outburst measurement, except that the total exposure time was longer, and no separate background measurement for the high resolution module was obtained. The pre-outburst spectra were extracted in an identical way as our outburst spectra, with the exception that for the high-resolution spectra the background emission was removed by fitting a local continuum underneath the source profile.

1.2 Alternative scenarios to on-going crystal formation

One may wonder which other possible scenarios, apart from formation of new silicate crystals, could have produced the observed peaks in the outburst Spitzer IRS spectrum. We investigated two alternative scenarios, both of which assume that crystals already existed in the disk before the outburst and they were not created in the recent eruption.

In the first scenario the crystals are located in the disk midplane, where they were created earlier due to viscous heating. These crystals were stirred up to the disk atmosphere in the 2008 outburst, where they became visible for infrared spectroscopy. We studied the validity of this scenario by calculating the turbulent mixing timescale required to move a dust grain from the disk midplane to the disk atmosphere. It can be seen in Fig. 2 that the resulting timescales are longer, even for the strongest possible turbulence, than the approximately three months elapsed between the beginning of the outburst and the Spitzer IRS measurement.

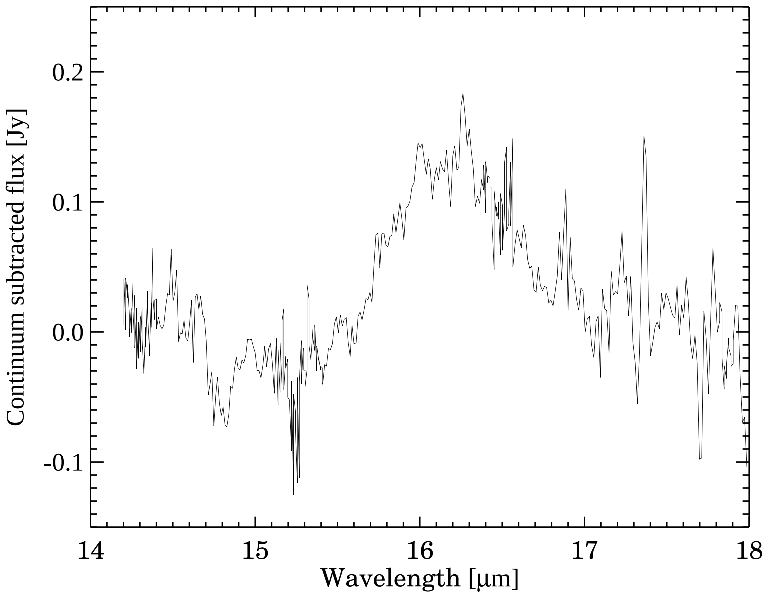

Figure 1: *The crystalline silicate peak at 16 µm in the outburst spectrum. Continuum fluxes in the ranges of 14.2–15.0 µm and 17.2–18.0 µm were fitted by a second order polynomial and subtracted from the data.*

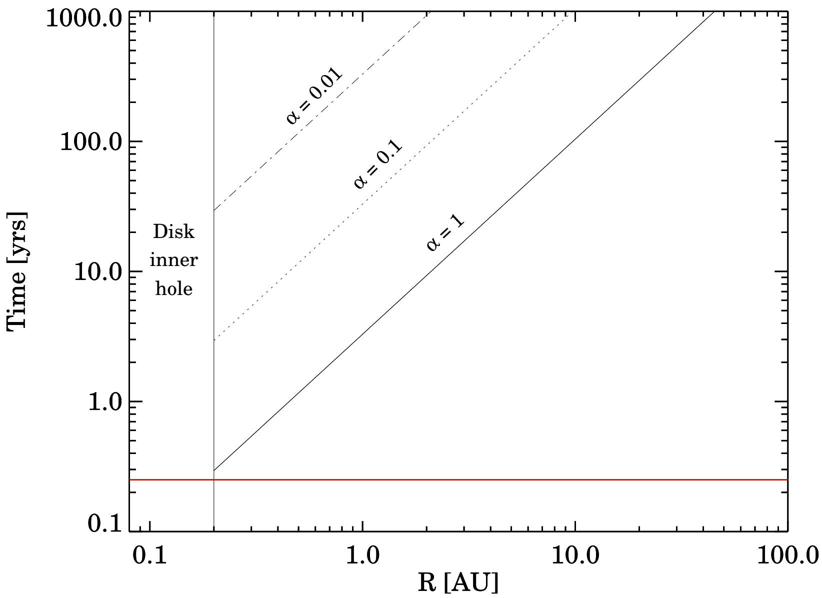

Figure 2: *Timescale for mixing up a dust particle vertically from the mid-plane to the disk atmosphere, as a function of the distance to the central star in the plane of the disk, for different values of the turbulent viscosity parameter α. The horizontal red line is set to 3 months, the time elapsed between the beginning of the outburst and our Spitzer IRS measurement.*

The other scenario assumes that the existing crystals were already located in the disk atmosphere in the outer disk and the outburst only illuminated and not created them. In the quiescence the temperature of the crystals should be low enough to prevent the crystals to produce mid-infrared features in the IRS wavelength range (5.5–38 μm). In order to avoid the appearance of the strong 33 μm band, the temperature of the silicate crystals should be lower than 100 K. In the outburst the temperature will rise in the whole disk due to the enhanced irradiation luminosity, making the crystals hot enough to produce mid-infrared features. Since in the outburst spectrum we do not see any crystalline feature longwards of 16 μm, the crystals should be very hot (>700K) in order to avoid the appearance of the strong bands at 24 μm and at 33 μm. If the above described illumination effect would be the explanation of the difference between the outburst and quiescent phase spectra, the temperature of the crystals should change by more than a factor of 6. Since the temperature in the disk is proportional to the square-root of the irradiation luminosity, this temperature difference indicates a luminosity change of more than a factor of 36. This is by far above the observed change in the infrared luminosity, which is directly proportional to the irradiation luminosity. Thus in our view the only possible scenario is that crystals are formed in-situ during the outburst in the upper layer of the disk of EX Lup.

1.3 The EX Lupi system

EX Lupi is an M0V star at a distance of about 155 pc. According to our modeling[17], performed with the radiative transfer code RADMC[29], the star harbours a circumstellar disk which is passively heated by the radiation of the star. Accretion heating in the mid-plane of the disk turned out to be insignificant both in quiescence and in outburst. The geometry of the disk is depicted in Fig. 3. It is a moderately flaring disk with a mass of 0.025 $M_{\odot}$. The inner dust-free hole has a radius of 0.2 AU, which is larger than the sublimation radius of silicate grains (0.05 AU), thus the origin of this large hole is unclear.

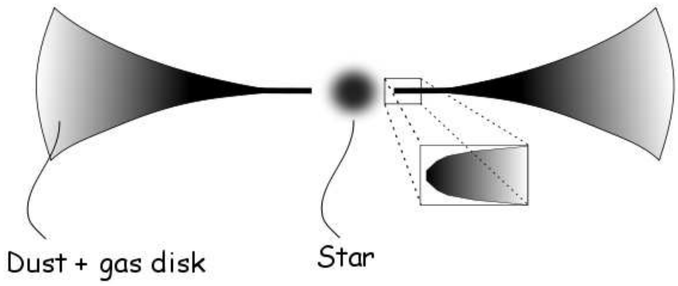

Figure 3: *Schematic picture of the geometrical structure of the EX Lupi system in quiescent phase.*

The radial temperature profiles of the disk in quiescence and in outburst are shown in Fig. 4. In quiescence the surface temperature was almost everywhere below 700 K, only in a narrow ring located at the inner edge of the disk ($0.2 < r < 0.21$ AU) increased the temperature to $T \leq 900$ K. In outburst the whole disk became hotter and the inner 0.5 AU area was heated above 1000 K, making possible crystal formation. The temperature nowhere exceeded 1500 K, the sublimation threshold, except at the inner edge of the disk where it reached a peak temperature of 1700 K. The mid-plane remained below the crystallization temperature both in quiescence and outburst.

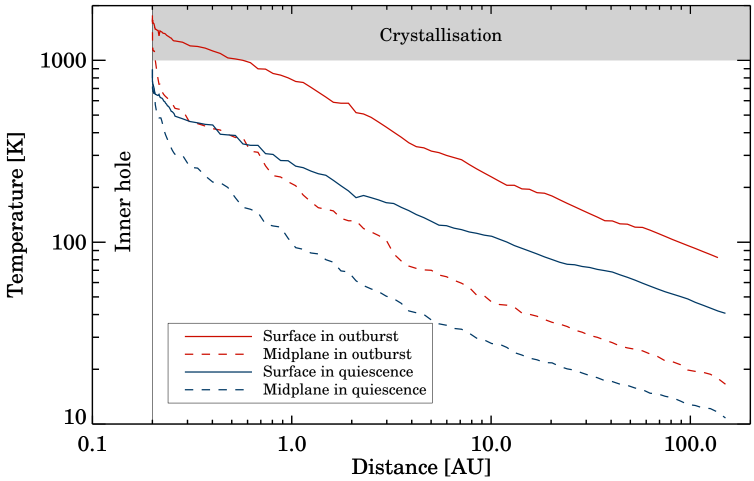

Figure 4: *Radial temperature profile of the disk surface (continuous line) and the disk mid-plane (dashed line) in quiescent phase (blue) and in outburst (red). The radius of the inner dust-free hole and the temperature range where crystal formation may take place (T> 1000 K) are marked.*

1.4 The outburst history

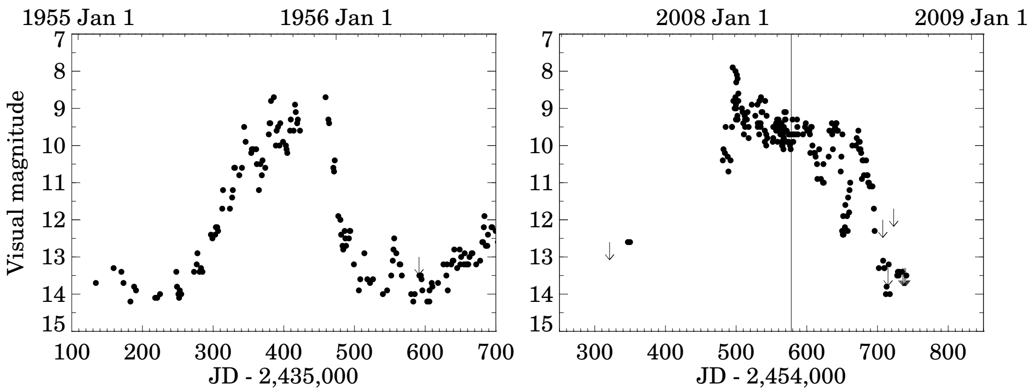

Figure 5: *Light curve of EX Lup compiled from visual estimates. Left: the outburst of EX Lupi in 1955-56. Right: the recent outburst in 2008, taken from data at www.aavso.org. The peak brightnesses and the characteristic timescales were similar in the two eruptions. Our Spitzer observation was obtained on 2008 April 21, marked by the vertical line in the figure.*

The present outburst was not the first one in the life of EX Lupi. Beside smaller scale flarings by factors <10, it had a major eruption in 1955-56, when the peak visual brightness reached 8.5 magnitude, very close to the maximum of the present outburst[7] (Fig. 5). The comparable peak luminosities in the two eruptions imply that the disk areas heated above the crystallization threshold were also similar. Since crystallization above 1000 K is an almost instantaneous process, it is the maximum illuminated area, rather than the duration of the brightness peak, which determines the crystal yield. It is then reasonable to assume that very similar amounts of crystalline silicate were formed in the two eruptions, and the shape of the silicate profile in early 1956 would have looked similar to the one we measured in 2008 April.

1.5 The disappearance of crystals after outburst

Because the silicate profile in early 1956 should have probably looked similar to the one measured in 2008, it is surprising that by 2005, the date of the quiescent Spitzer spectrum, the crystalline spectral features vanished. Possible explanations are vertical mixing in the disk which transports the crystals into the disk interior; inward surface flow which may accrete them onto the star; or amorphization of crystals by cosmic rays or X-rays. Exploring the first scenario, we computed time-scales for vertical mixing of grains over the width of the surface layer (the disk interior is probably mainly amorphous, as indicated by the quiescent spectrum), for different values of α, the viscosity parameter in the standard alpha-prescription of disks (Fig. 6). On theoretical basis, the value of α lies between 10^{-5} and 1, higher values corresponding to higher levels of turbulence. Though its value is fundamental in hydrodynamic simulations of planet formation, only very weak observational constraints exist. Adopting the 50 year interval between the two major outbursts of EX Lupi as an upper limit for crystal removal, Fig. 6 constrains α to be higher than 10^{-4}. This is a plausible result, indicating that vertical mixing can be an explanation for the quick removal of crystals. The inward surface flow scenario might also explain the disappearance of crystals. Surface flows are predicted in two-dimensional transport models of viscous protoplanetary disks[20,30]. Based on these simulations we estimated that the inward surface velocity is approximately 0.0006 AU/yr for the gas component. Assuming that the crystals are coupled to the gas, in 50 years they could proceed 0.03 AU, one order of magnitude less than the size of the crystallized zone of 0.5 AU in EX Lup. This estimate, however, depends on the exact choice of α (assumed to be 0.001 in the mentioned simulations), and higher α values would result in higher surface flow velocities potentially able to accrete the fresh crystals onto the star within 50 years. Note, however, that 50 year is only an upper limit for crystal removal, and also that in detailed modeling the differences between gas and dust velocities have to be taken into account.

1.6 On the variability of young stars

Photometric variability is typical of most pre-main sequence stars with and without disks[24,31]. Accretion is a very dynamic process in classical T Tauri stars (CTTS)[32], being one of the leading causes of strong, non-periodic variations. Accretion-related hot spots, together with variable extinction caused by circumstellar material in nearly edge-on systems, cause photometric variations in most of the young CTTS[24]. Both variability mechanisms can be distinguished by observing the colour changes and accretion indicators (e.g. accretion-related emission lines). Photometric monitoring of large samples of CTTS over years/decades[24,33] reveals that more than 50% of the CTTS with ages 1-3 Myr exhibit variations over 1 magnitude in the V band, and 10% of them experience even larger variations (ΔV$\leq$1.5-2 mag). Although objects with low-amplitude variations display typical variability patterns that change little during years/decades, the most extreme variables are typically erratic[33], so stars with large variations also have epochs with lower-amplitude variability. In addition, the amplitude of the variations measured is always a lower limit, since the light curve changes can be very fast. Therefore, accretion variations and small accretion outbursts may be common for a large fraction of pre-main sequence stars during their first Myrs of life.

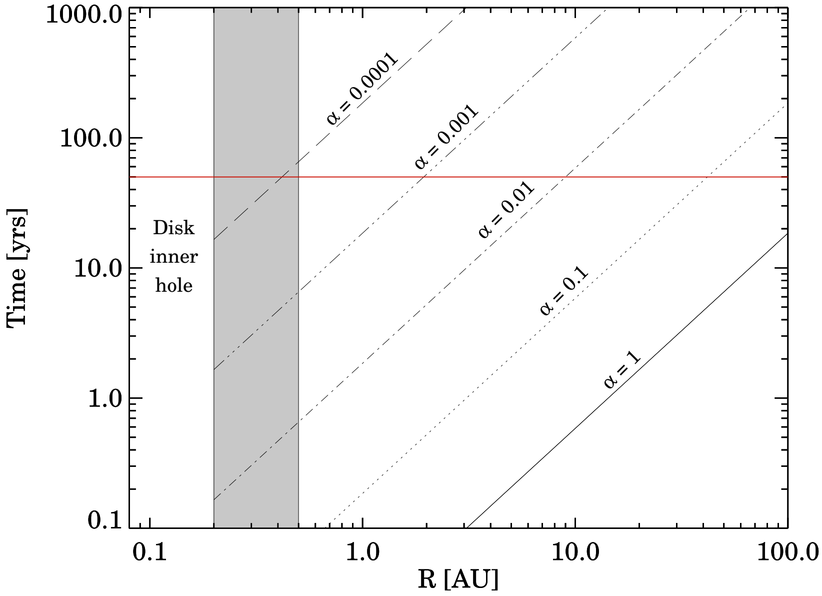

Figure 6: *Vertical mixing timescale as a function of the distance to the central star in the plane of the disk, for different values of the turbulent viscosity parameter* α. *The shaded area marks the disk region where the temperature is sufficiently high for crystallization during outburst. The horizontal red line is set to 50 years, the time elapsed since the last outburst of similar magnitude.*

2 Supplementary Notes

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