High Temperature Silica in Protoplanetary Disks

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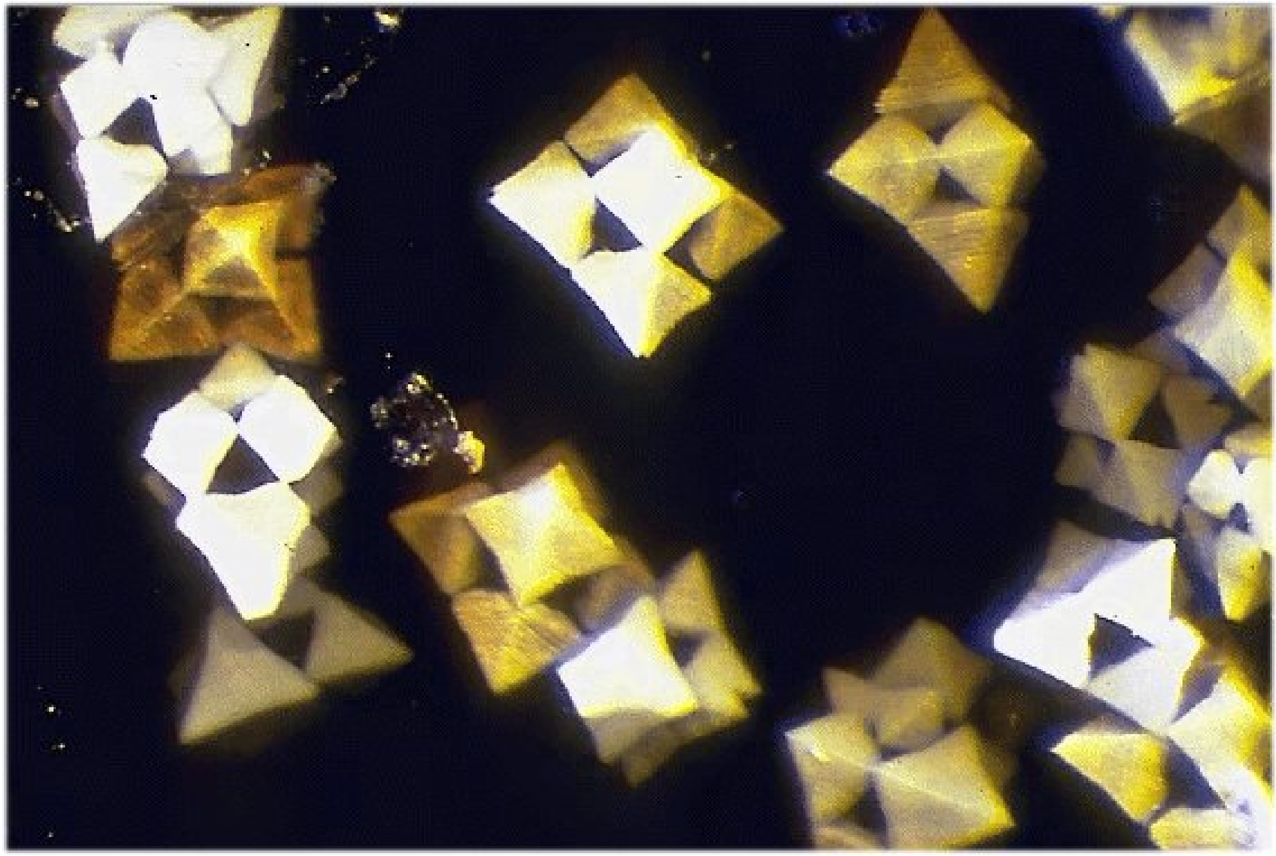


Cristobalite crystals from Mexico

http://webmineral.com/specimens/picshow.php?id=291
Comments: White crystals of cristobalite frozen in obsidian glass.
Location: Cerro San Cristobal, Pachuca, Hidalgo, Mexico.

Outline

- *Spitzer*-IRS observations of dust emission from T Tauri stars.
- **Prominent features at 9.1, 12.6, and 20 μm ➔ silica**
  - **Select 5 silica exemplars from ~ 200 high-quality spectra**
    - **IRS_Disks GTO program**
- Each polymorph of silica (SiO_2) has a distinct spectrum
  - α & β quartz, tridymite, cristobalite, amorphous
- χ^2 minimization 2 Temperature model applied
  - In each case, annealed silica provides best fit
    - Baked at 1220 K for 5 hours
    - Mostly cristobalite, some tridymite (high temperature polymorphs)
- Polymorphs metastable at lower temperatures

Two temperature (warm & cold) model

$$F_\nu(\lambda)^{\rm mod} = B_\nu(\lambda, T_c)\left[\Omega_c + \sum_i a_{c,i}\kappa_i(\lambda)\right] + B_\nu(\lambda, T_w)\left[\Omega_w + \sum_j a_{w,j}\kappa_j(\lambda)\right] ,$$

κ(cm^2/gm) are small grain opacities, a's are the mass/d^2 of that component. Solid angles represent optically thick disk + carbon + very large silicates.

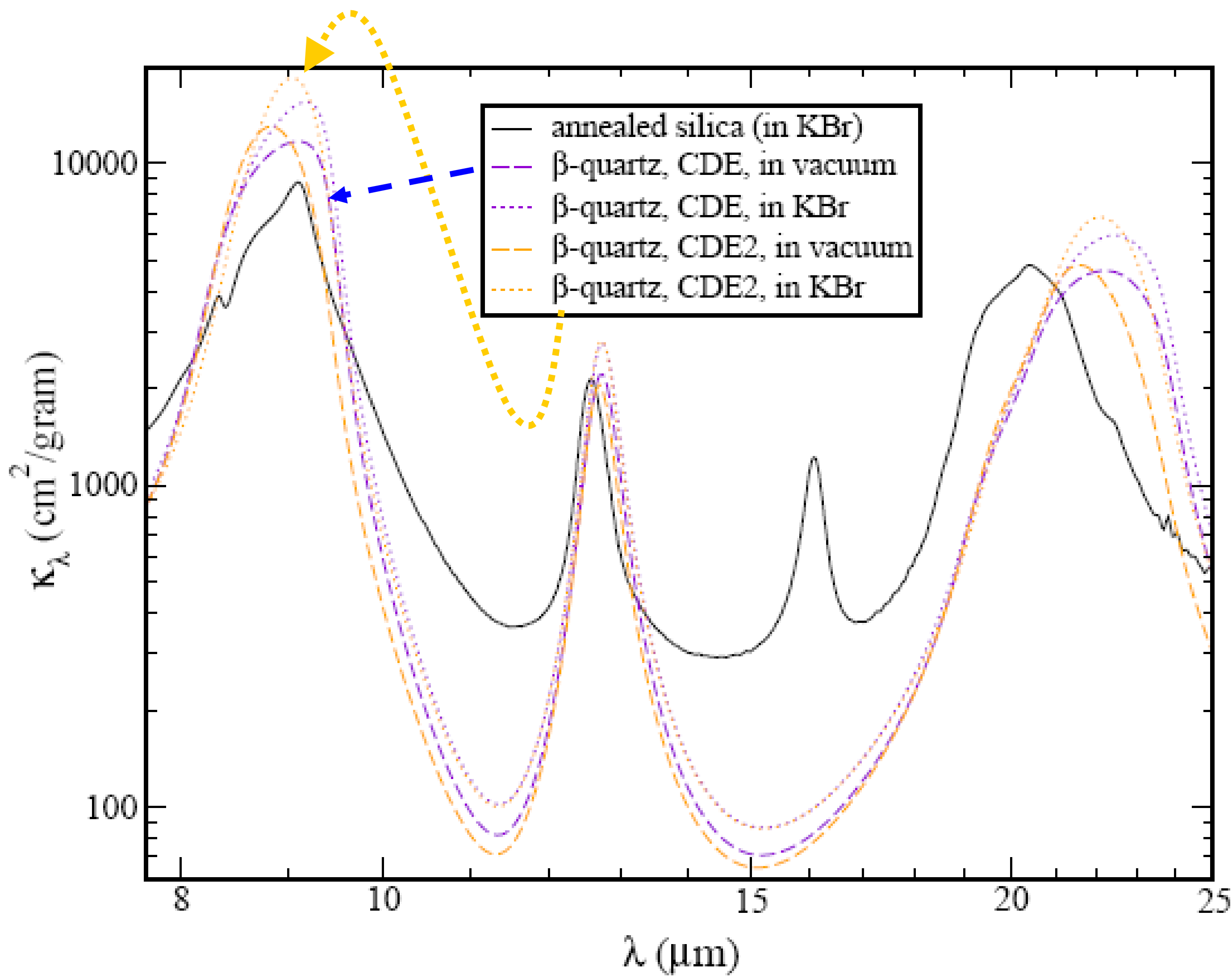
Silica modelled previously as either α quartz (Bouwman et al. 2001, Honda et al. 2003) or amorphous silica (Bouwman et al. 2007)

Model tested against full self-consistent radiative transfer model on IS Tau (Sargent et al. 2006).

Our annealed silica opacity comes from ground up particles embedded in KBr (Fabian et al. 2000). We tested that effect by calculating the opacities of small β quartz grains (CDE and CDE2) embedded in KBr, using Mie theory.

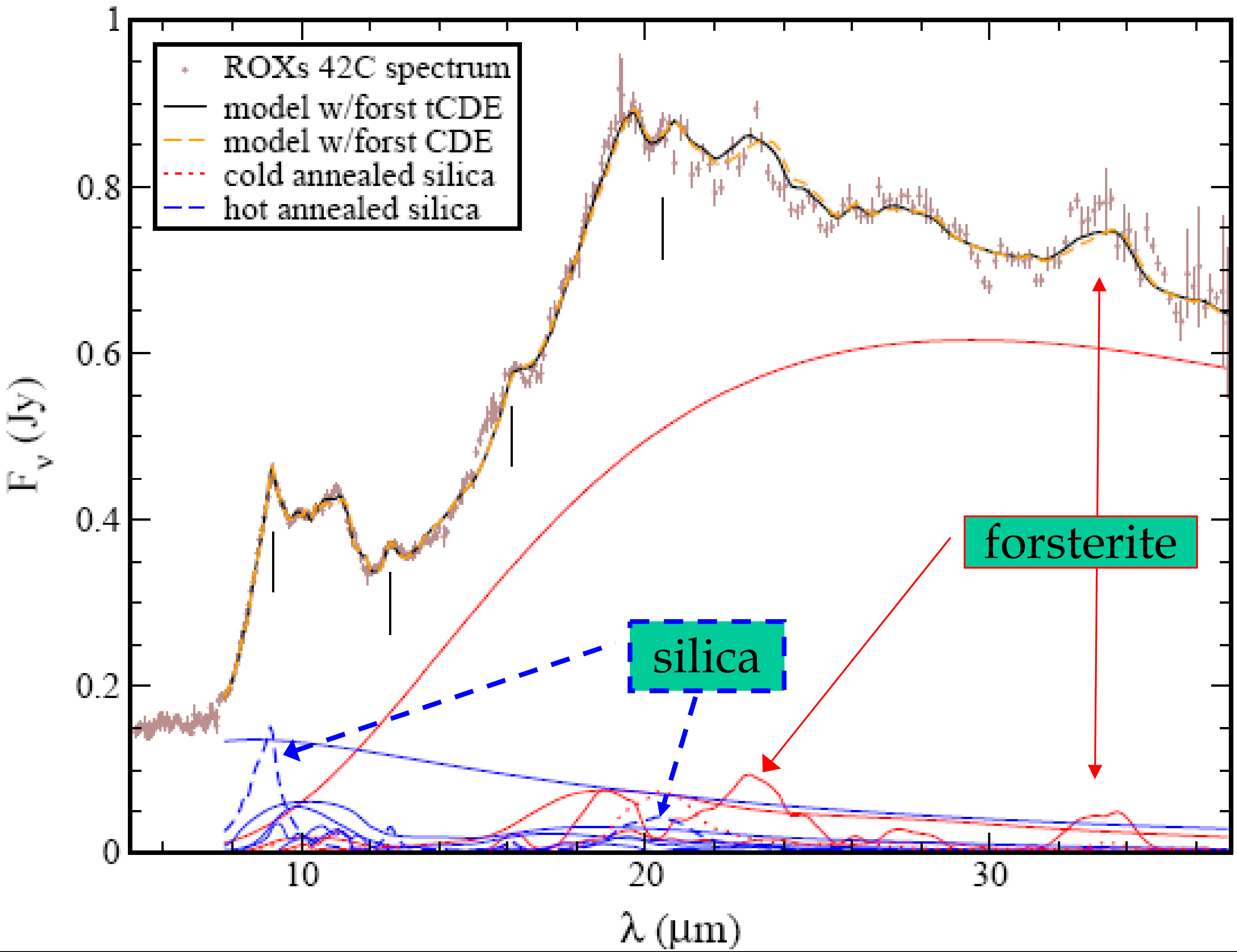
The isolated 12.6 μm feature is unchanged. The change in the stronger 9.1 and 20 μm features acts like shape (CDE2 in KBr looks like CDE in vacuum).

Test of KBr effect

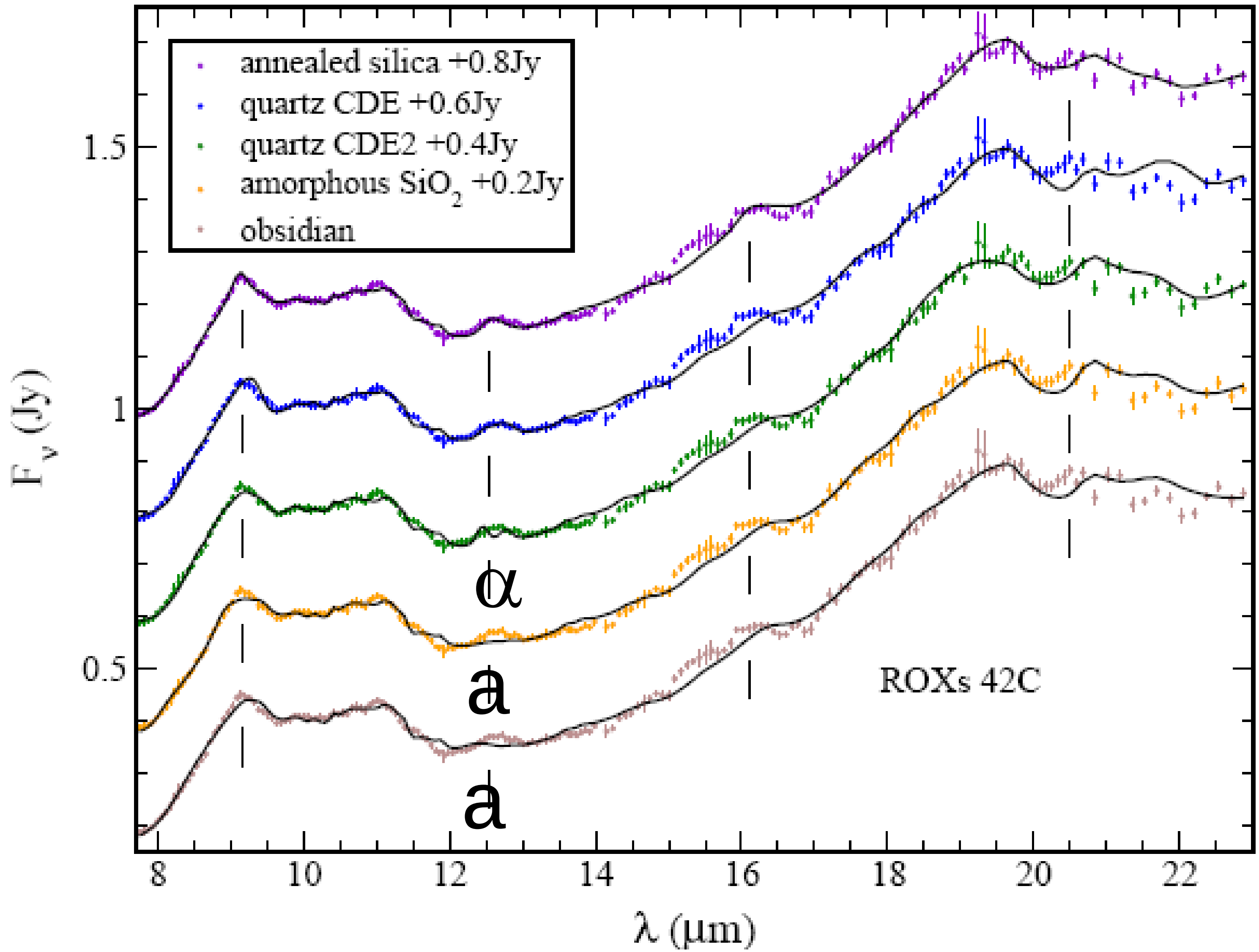


ROXs 42C fit with annealed silica (vertical bars)

In addition to the prominent silica features, our stars show evidence of amorphous silicates (large and small) , forsterite, and enstatite. By tuning our opacities for these components, we effectively isolate the silica features.



Test of silica polymorphs

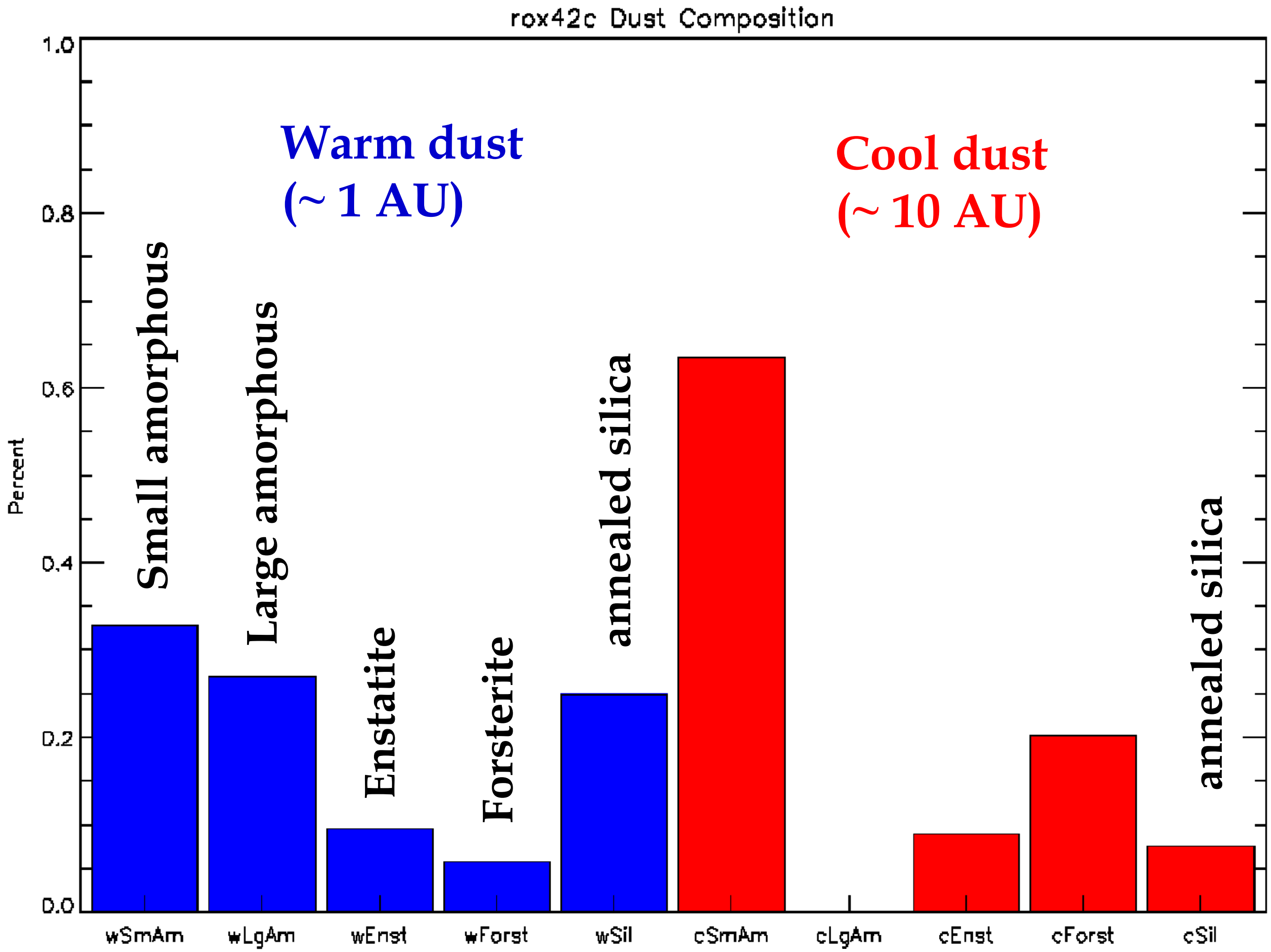


The best fit is given by the annealed silica (mostly cristobalite with some tridymite) produced by Fabian et al. (2000). It was cooled at 2000-50 K/hr, rapid enough to quench the metastable structure.

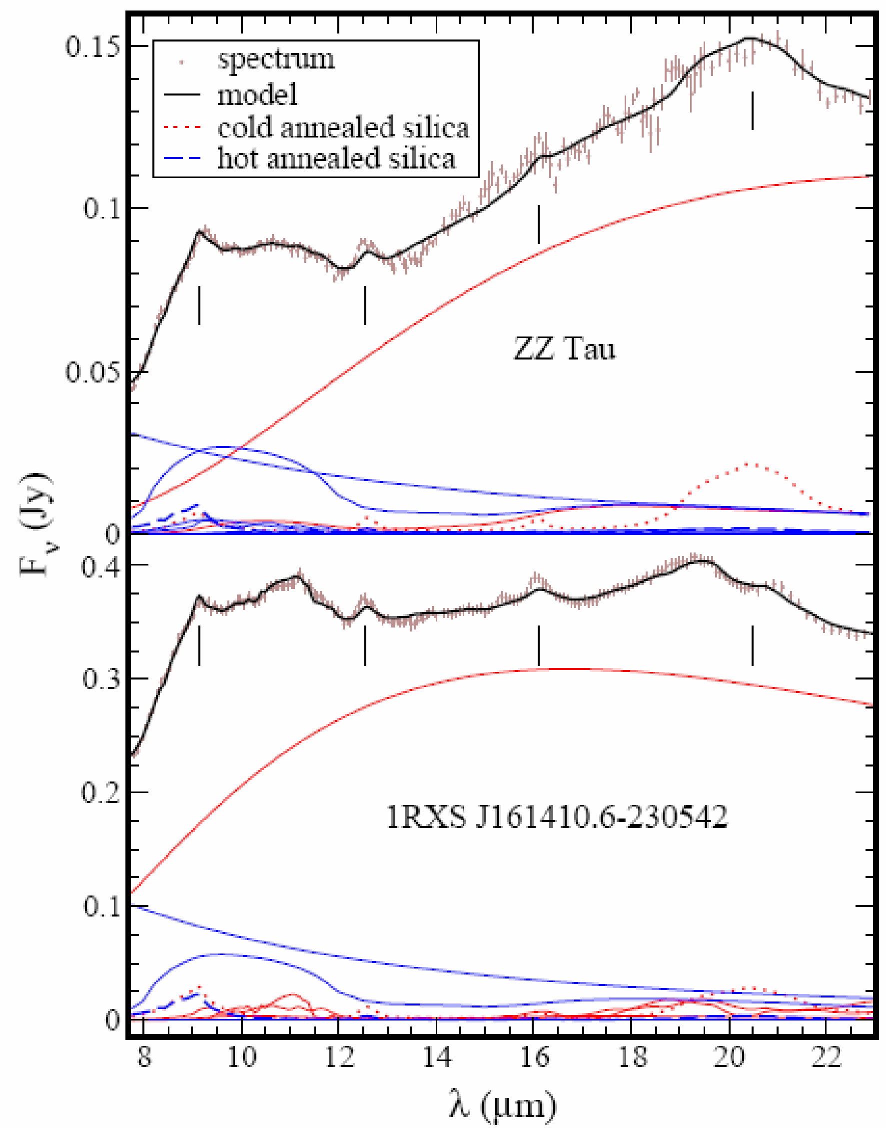
ROX 42c Dust Fingerprint

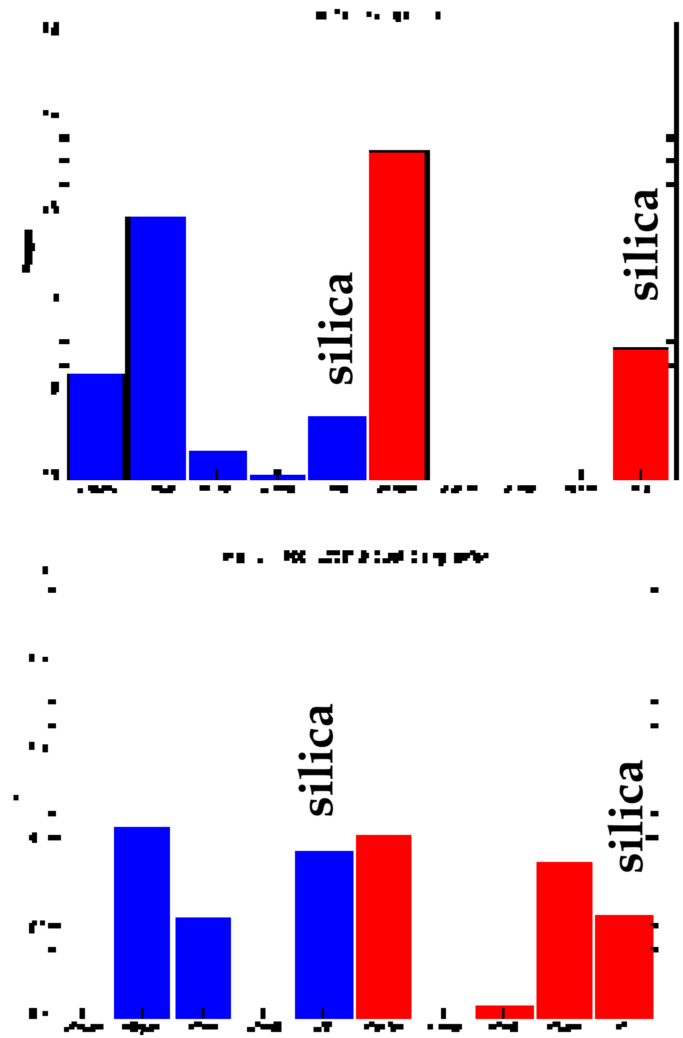
Quick summary of the derived dust composition. Fraction by mass of each of the major warm (w) and cool (c) components.

Silica is the rightmost column (warm in blue, cool in red)

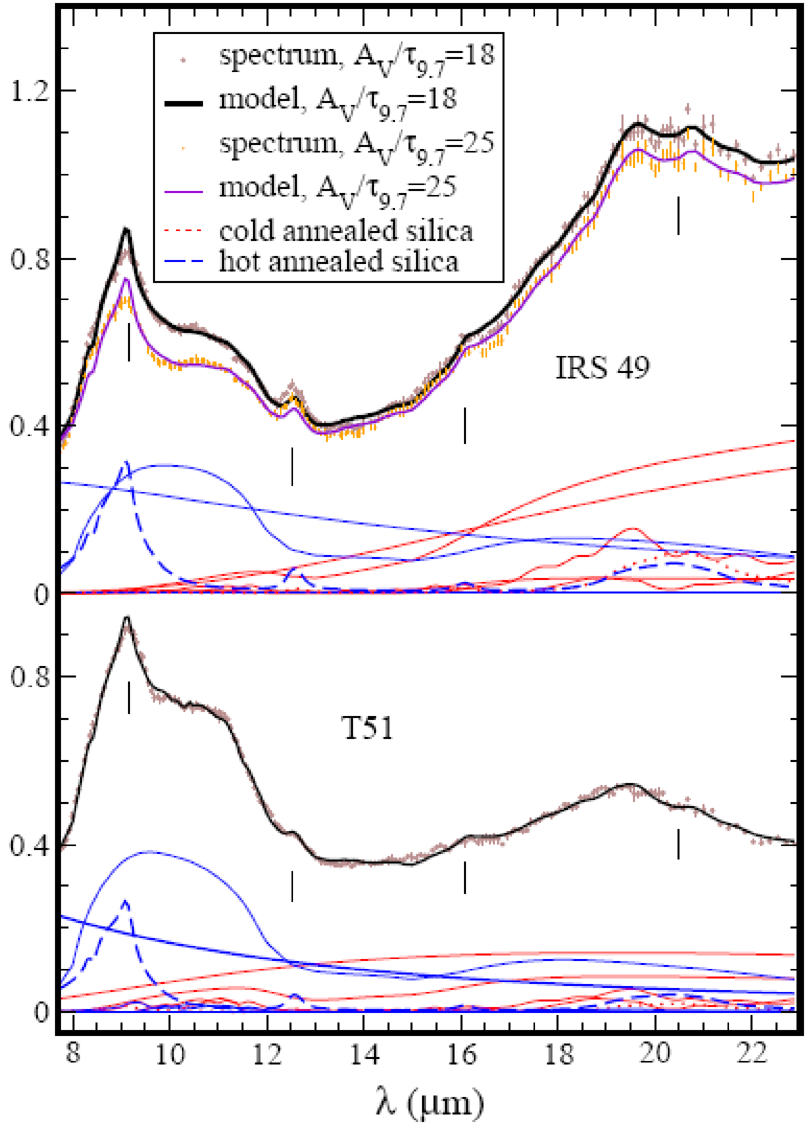


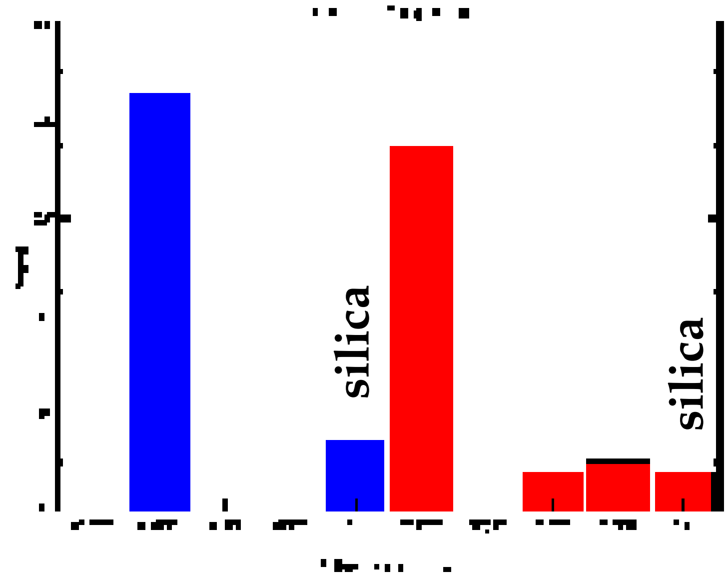
Exemplars fit with annealed silica

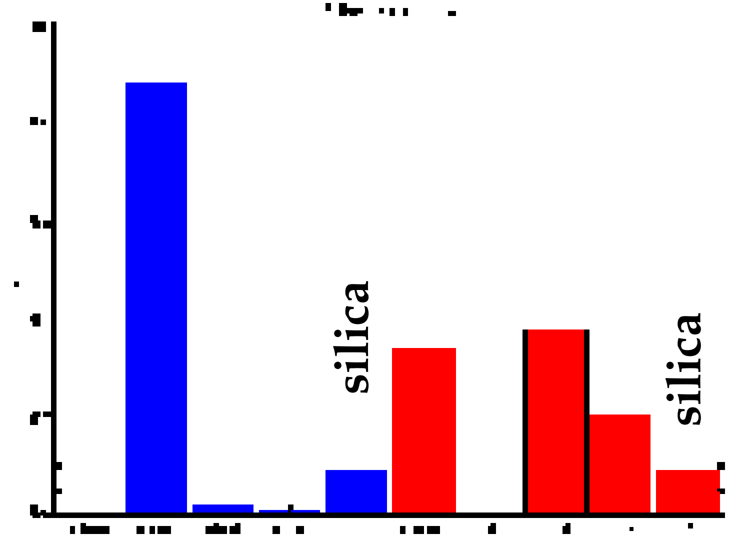




Exemplars fit with annealed silica



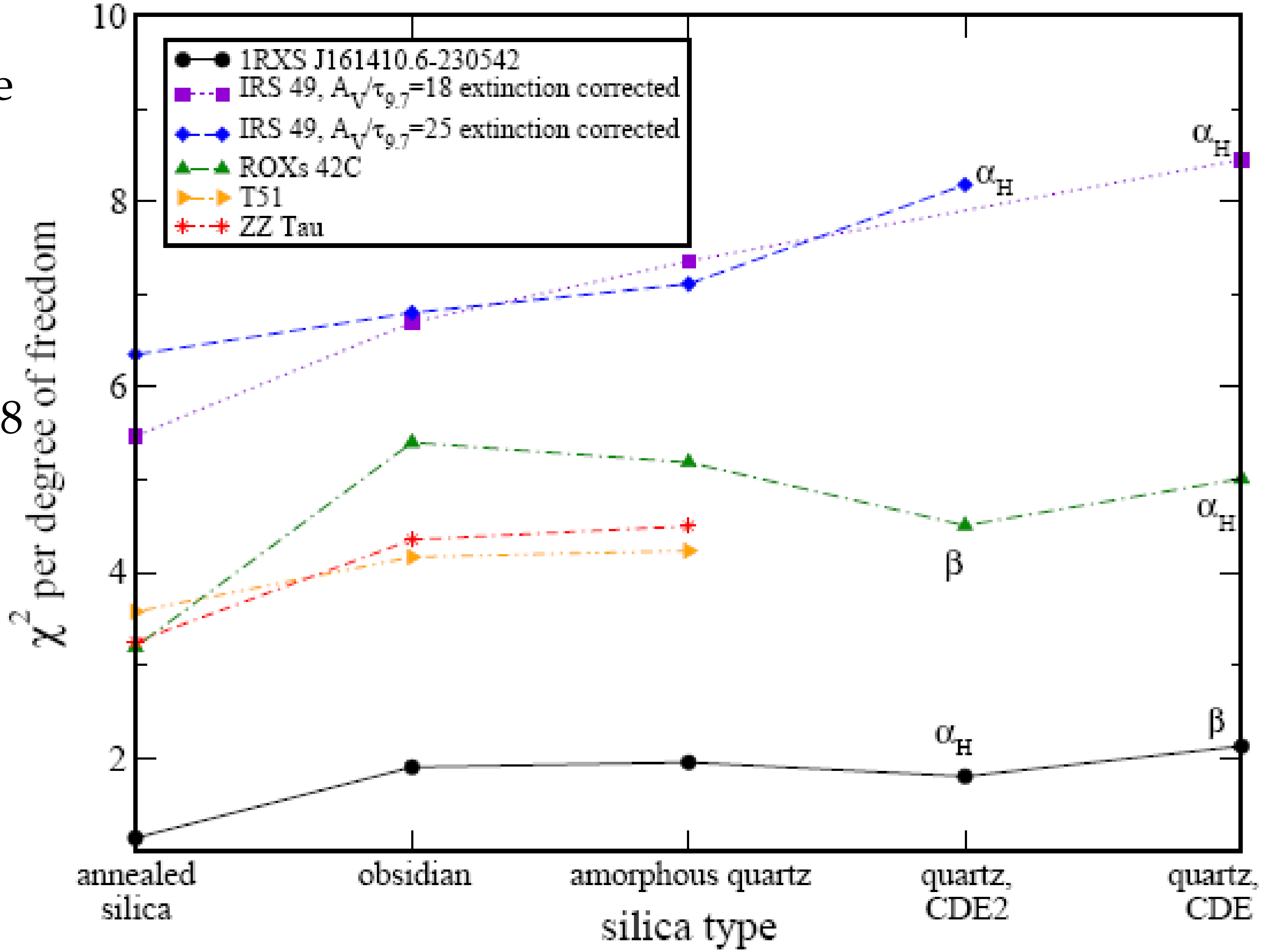




χ^2 test of various silica's

In each case, the best fit is given by annealed silica. The $\Delta\chi^2$/dof measures the formal significance of the improved fit. An increase by one is significant at the 5-8 σ level.

More significant is the fact that for all five silica exemplars, annealed silica provides the best fit.



Phase Diagram of silica

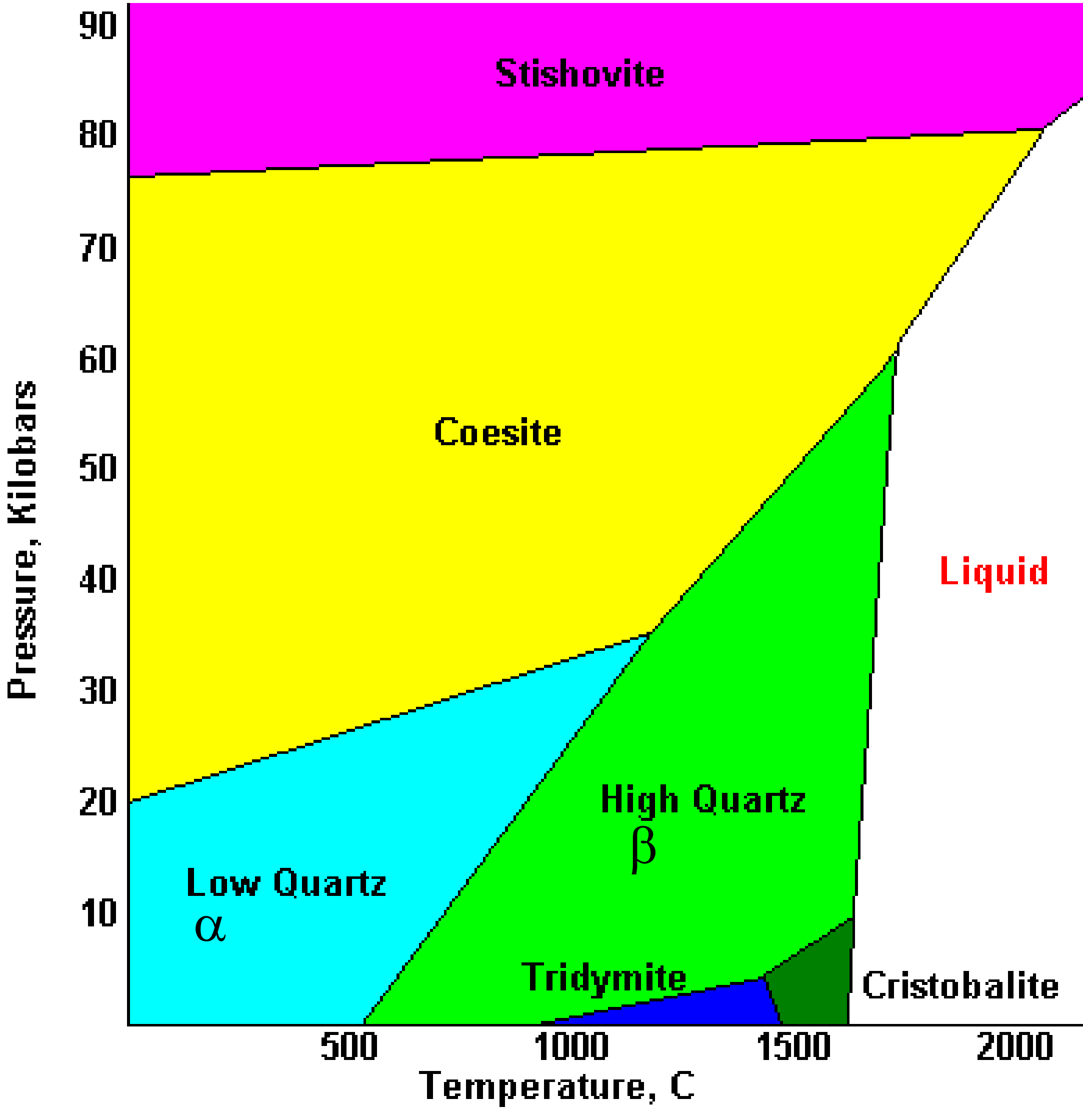
High pressure forms (Coesite and Stishovite) are definitely ruled out by the IRS spectra.

As temperature increases, α Quartz converts to β, then Tridymite and Cristobalite.

If Tridymite/Cristobalite are kept for a long time just below 845 K, they will revert to a Quartz.

Preservation of the high temperature forms of silica requires somewhat rapid cooling (quenching) – not likely for production near the dust sublimation radius.

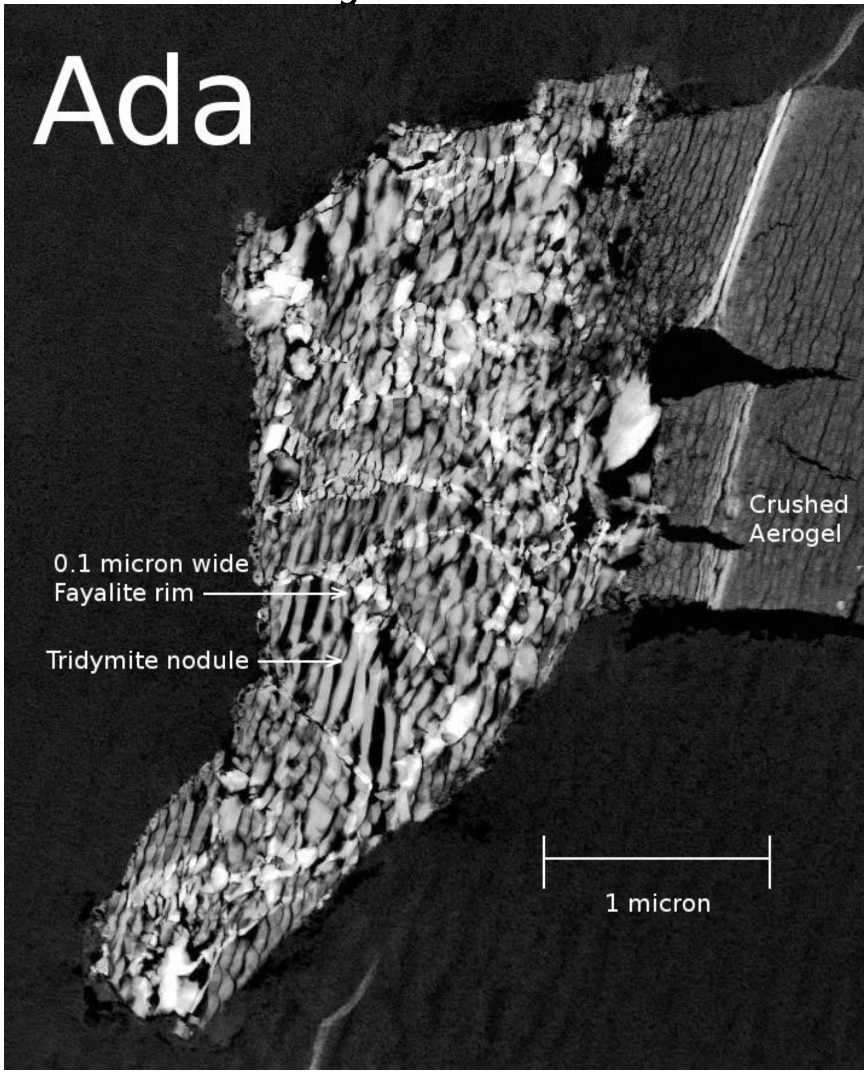
Flash-heating in the outer disk is indicated



Silica from comet Wild 2 is tridymite

This, and a second grain (Mikouchi et al. 2007) from Wild 2 (Stardust mission), both indicate the high temperature forms of silica (cristobalite and tridymite). This suggests the dust processing in the solar nebula 4.6 Gy ago was similar to what we're seeing in 1-3 My old protoplanetary disks right now.

The identification of the high temperature forms of silica in this comet (and enstatite chondritic meteorites, e.g. Dodd (1981), strengthens our identification of annealed silica from the Spitzer IRS spectra of protoplanetary disks.

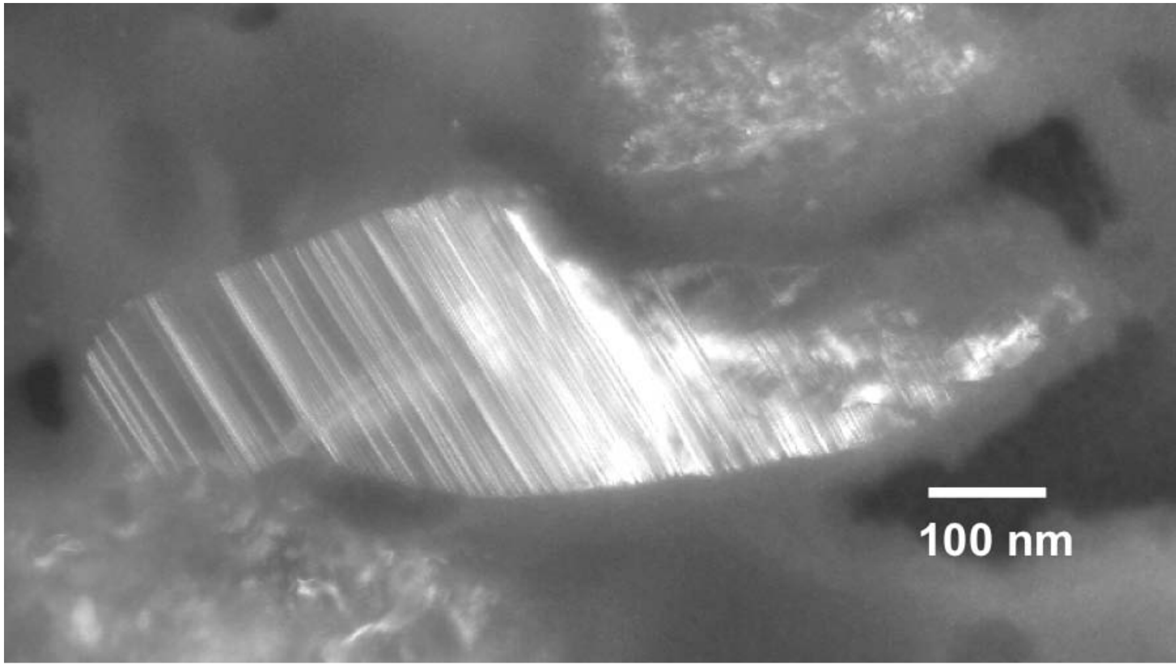


Courtesy Dave Joswiak, U. Wash.

Enstatite in InterplantetaryDustParticles indicate flash-heating

Protoenstatite (T > 1258K) is unstable at lower temperatures. When cooled, it will revert to ortho then clinoenstatite. The clino/ortho ratio depends on the cooling rate. For 75% clino, the implied rate is ~ 1000 K/hr.

Note: our best fitting enstatite is clino – it could have resulted from rapid cooling of protoenstatite

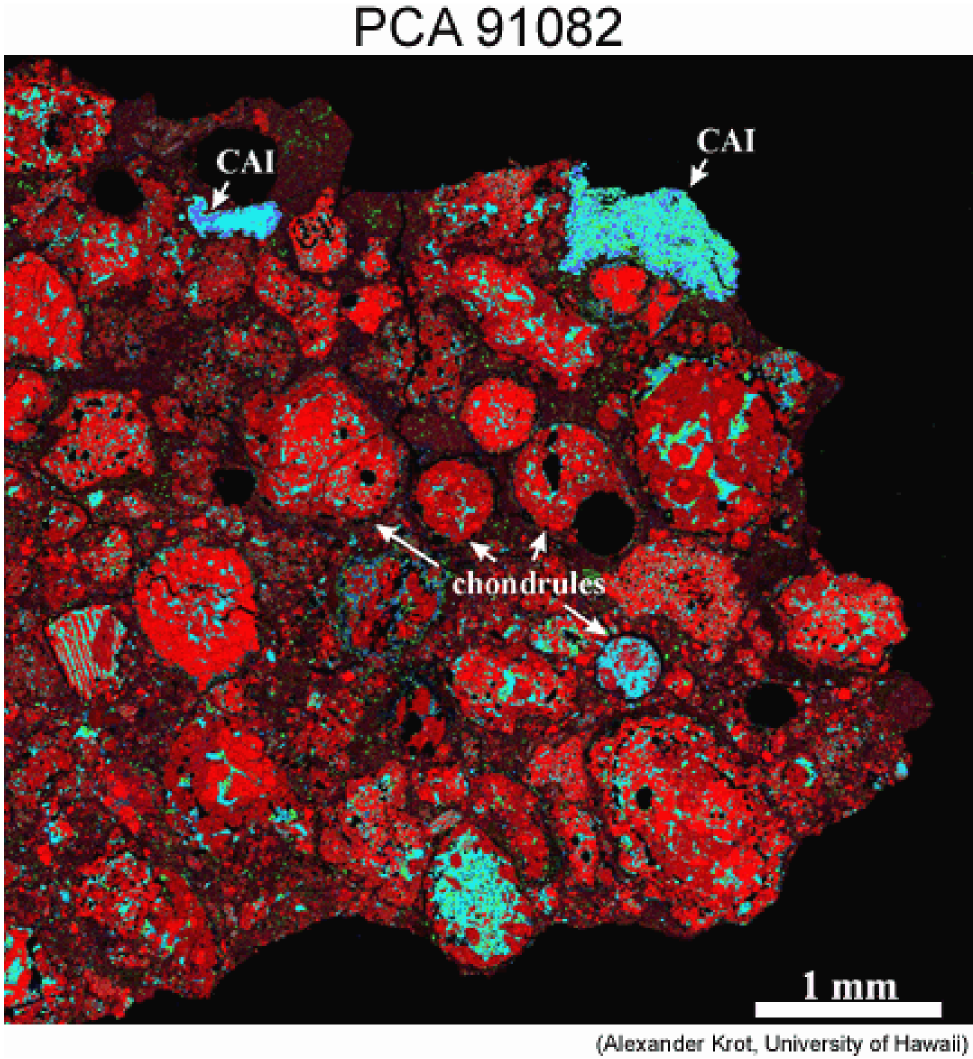


Alexander et al. PPV 2006: A typical isolated enstatite grain from a chondritic porous IDP. The fine lamellae are the result of **relatively rapid cooling** through the protoenstatiteorthoenstatite (1258 K) transition (Bradley et al., 1983)

Chondrules and CAI's in Primitive Meteorites

Chondrules are spherical glassy igneous inclusions that required high temperatures to form.

- Because they are glassy they probably cooled very fast.
- Formed ~1.7 Myr after the CAI's (Amelin et al. 2002, Connelly et al. 2008).
- Chondrules, enstatite, and annealed silica all seem to require flash-heating
  - Shocks most likely
  - Giant planets forming?



(Sasha Krot, U. Hawaii)