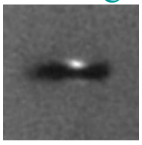
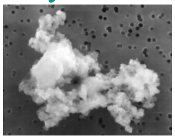
Comet Grains: Planet Formation as Told by the Tiniest Particles... Implications for Heating and Radial Mixing in the Protoplanetary Disk





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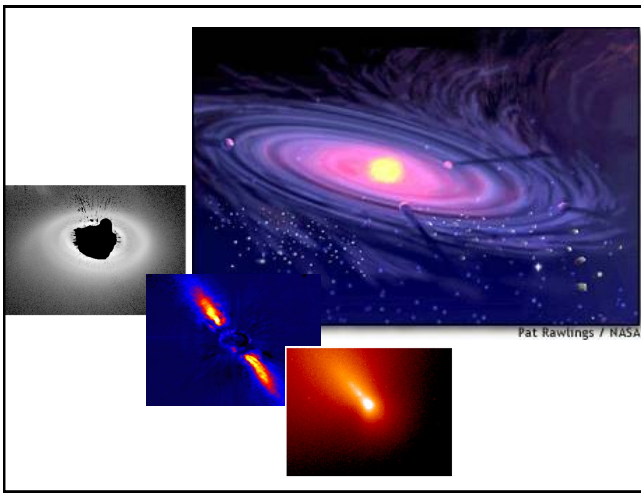
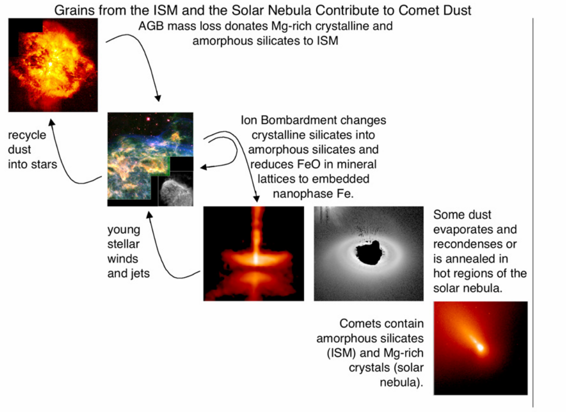
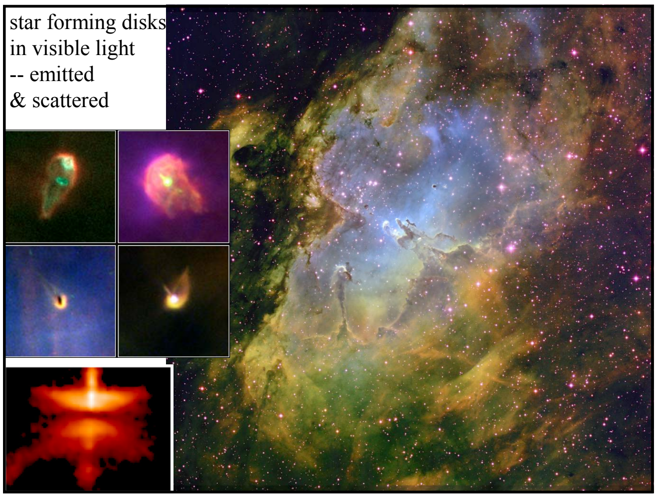
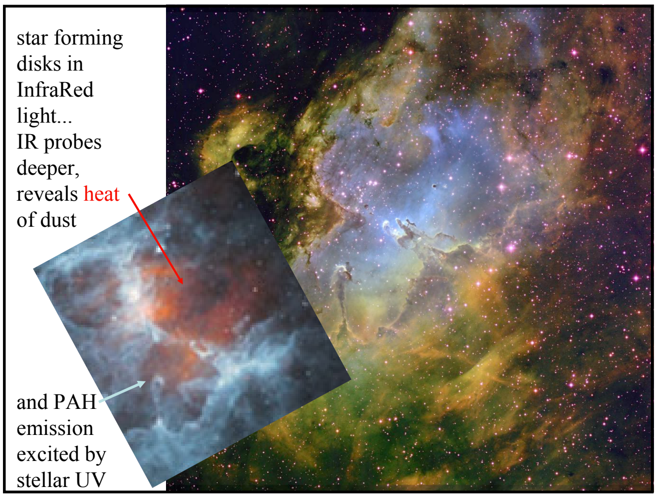
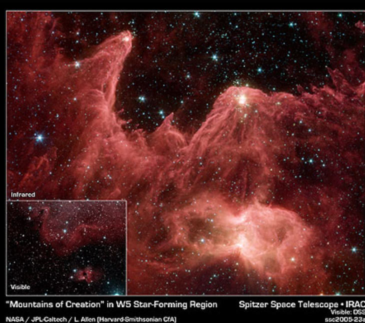


Comet grains constrain interstellar and solar nebula processes





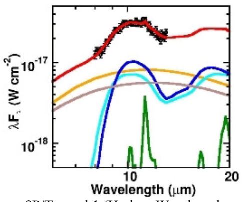




Comets are Astrophysical Laboratories for Studying Dust Grains

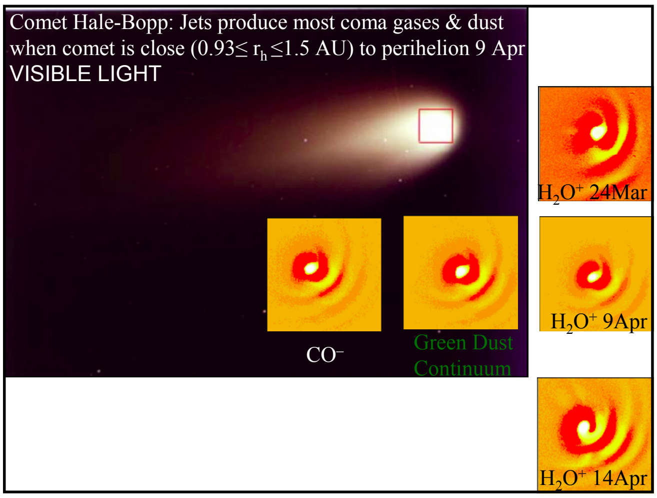
What is comet dust made of?

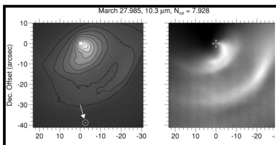
- Amorphous Fe-bearing silicates; porous – from ISM
- Abundant amorphous carbon (also seen in IDPs)
- Crystalline silicates (when detected) are:
  - submicron in size
  - **Mg-rich (>90%)**
  - comparatively cooler than the amorphous silicates
  - comparatively abundant



9P/Tempel 1 (Harker, Woodward, Wooden 2005, Science, 310, 278)

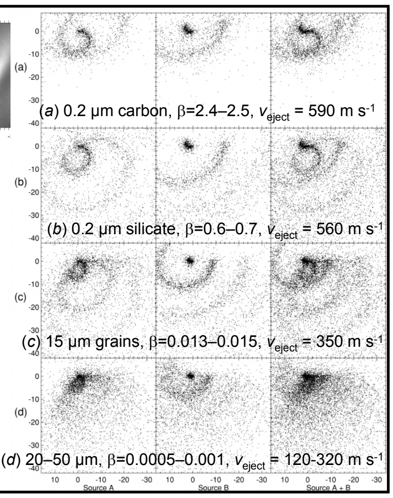
• NO layer-lattice silicates (e.g., Montmorillonite) and minimal Al_2O_3



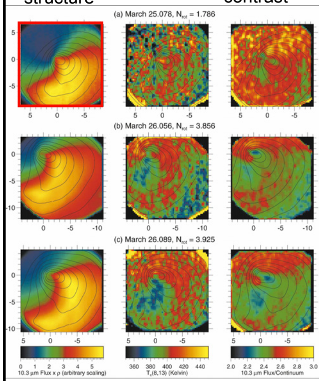


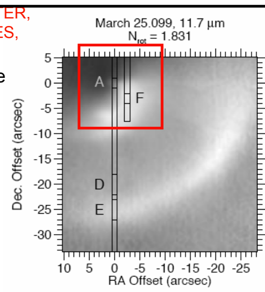
10μm INFRARED LIGHT

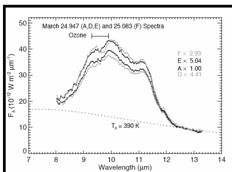
Grain composition and size can be investigated from the shape of the coma. $\beta = F_{radiation}/F_{solar\ grav}$ Arcs are best-fitted by submicron grains. Submicron silicate grains are less affected by radiation pressure than submicron carbon grains: $\beta_{silicate} < \beta_{carbon}$



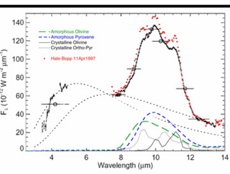
INFRARED: SMALLER GRAINS ARE HOTTER, SHOW STRONGER CONTRAST FEATURES, AND ARE ON LEADING EDGE OF JETS



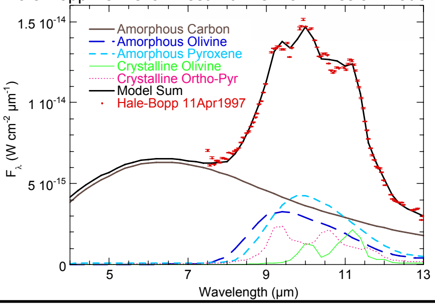


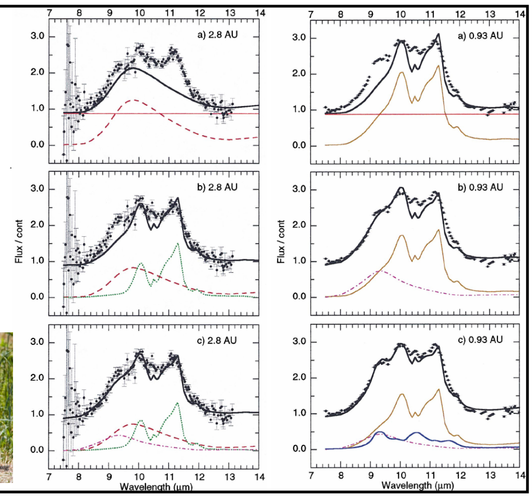


Hayward et al. 24 March 1997 compared to 11 April 1997: feature stronger at perihelion

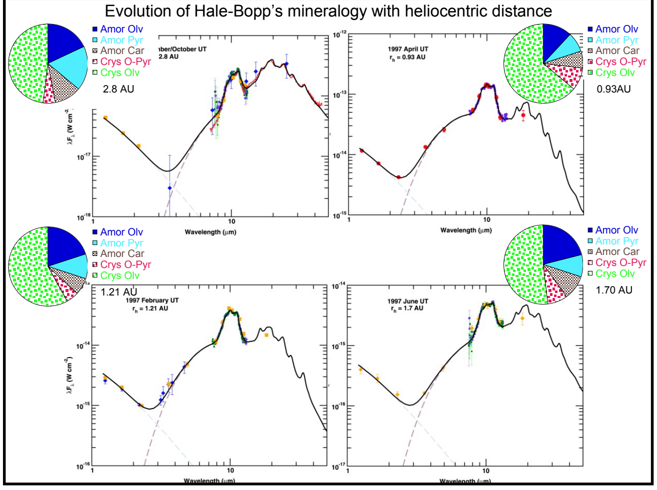


Hale-Bopp Perihelion Best-Fit Thermal Emission Model

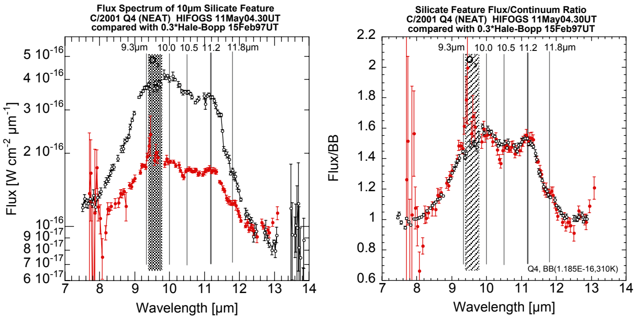




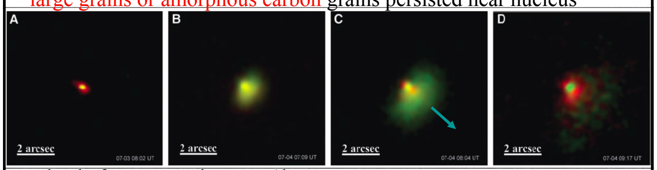
Evolution of Hale-Bopp's mineralogy with heliocentric distance



Oort cloud comet C/2001 Q4 (NEAT) has similar silicate mineralogy as Hale-Bopp; both have strong jet activity & crystal/amorphous ≈ 2. C/2001 Q4 has a smaller & variable silicate-to-amorphous carbon ratio, which lowers the contrast (height) of the silicate feature.



Deep Impact of Jupiter Family Comet 9P/Tempel 1: 8m-Subaru+COMICS 10μm Images show submicron grains released, large grains or amorphous carbon grains persisted near nucleus



day before | impact+1hr | impact+2hr | impact+3hr

inner coma structure falls off as 1/distance: gas `geyser' pushed grains into coma for about 2 hr

QuickTime™ and a Sorenson Video 3 decompressor are needed to see this picture.

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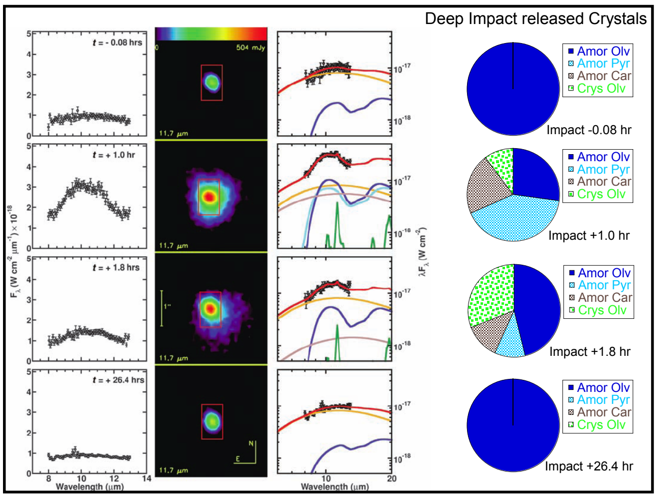
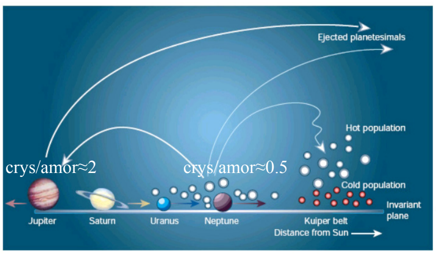
Deep Impact released Crystals



Comet Families



Oort cloud
Hale-Bopp
C/2001 Q4

Kuiper Belt
9P/Tempel 1

Outward radial transport?

Inward radial migration

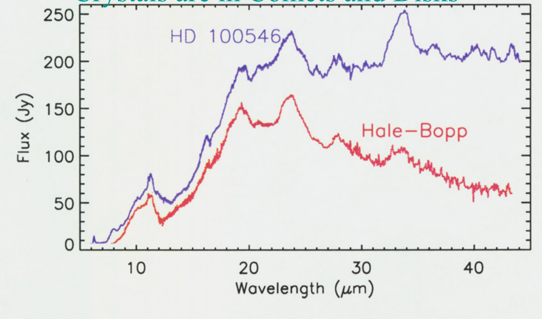
Morbidelli & Levison 2003

- Two primary comet families: long period Oort Cloud comets, and short period, Jupiter Family (JF) comets from the Kupier Belt.
- Both contain cold (<50K) nebular ices with ISM-like D/H and H_2O ortho/para ratios, implying this material was never heated
- JF comets suffer severe "weathering" that darkens and hardens the surface layers.

Crystals in Comets Suggest Possible Gradient in Early Solar Nebula

- Crystals > 2 in Oort Cloud comets, in Jupiter Family (9P) < 1
  - Possible evidence for radial gradient in disk
    - Outward radial migration
    - Inefficient annealing mechanism (?)
  - OR common heredity of Oort Cloud and 9P and not all crystals are revealed in 9P; 1/3 probability (Emel'yanenko et al. 2005)
- Need more observations of comets to better understand parent body processing

Crystals are in Comets and Disks

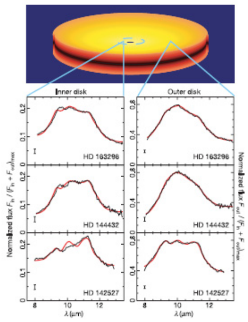


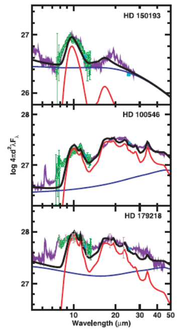
ISO Spectra of a Herbig Ae/Be star and Solar System Comet

(adopted from Crovisier et al. 1996, Science 275, 1904 and Malfait et al. 1998 A&A 332, 25)

Also see poster #557 – Kessler-Silacci et al. T Tauri Stars

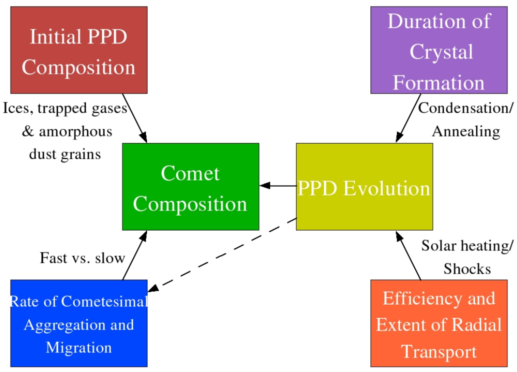
Crystal Enhancements in Inner Regions of PPDs



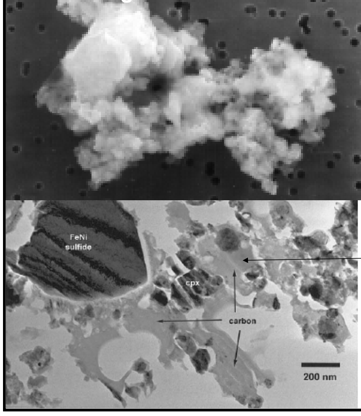


- Interferometry van Boekel et al. (2004); #582 crystals < 2 AU
- Modeling Harker et al. (2005) crystals < 5 AU

What Determines Comet Composition?



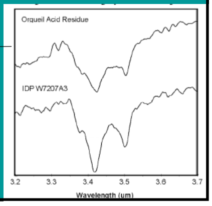
Anhydrous CP IDPs provide information about the Composition of COMETARY GRAINS and Thermal Processing of Sub-Grains



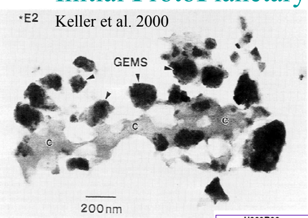
Cometary Anhydrous Chondritic Porous Interplanetary Dust Particles are highly porous aggregates of amorphous silicate spherules (GEMS), silicate crystals, “glued” together with Carbon

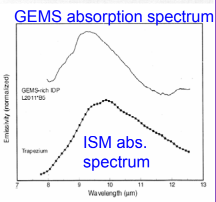
C can be amorphous, aliphatic, or aromatic

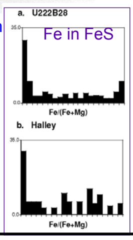
Aliphatic bond spectra of acid-etched IDP thin section



Initial ProtoPlanetary Disk Dust Composition







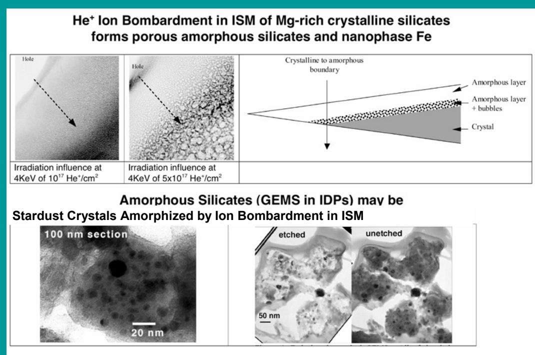
- Composed of ISM ice and dust grains
- Dust is abundant in Carbon
- Dust is abundant in Fe-bearing Amorphous Silicates: Amorphous Olivine and Pyroxene (GEMS-like grains)
- NO Crystalline Silicates

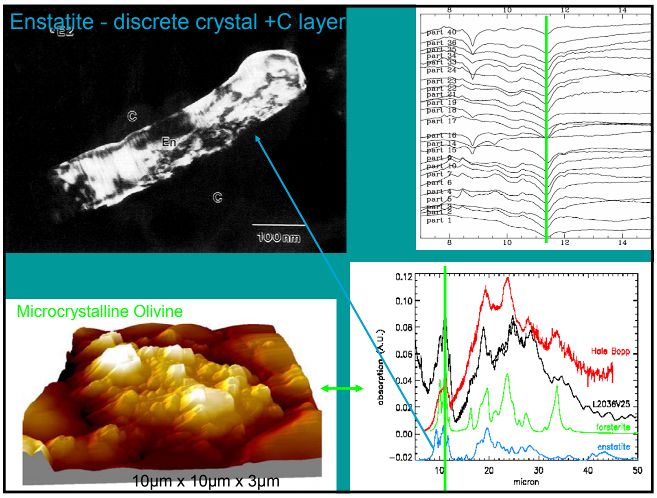
< 1% towards Galactic Center (Kemper et al. 2005)

< 5% line-of-sight in ISM (Li & Draine 2001)

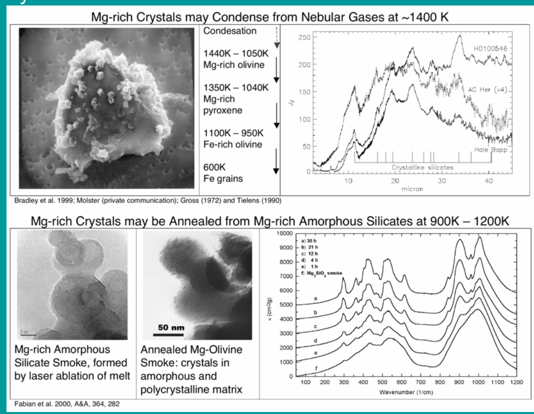
- Halley fly-by TOF MS measurements indicate 70% of Fe is in FeS grains, 30% in silicates

Amorphous Silicates in Comets are Relic Interstellar Grains: Stardust silicate crystals are *amorphized* by ion bombardment





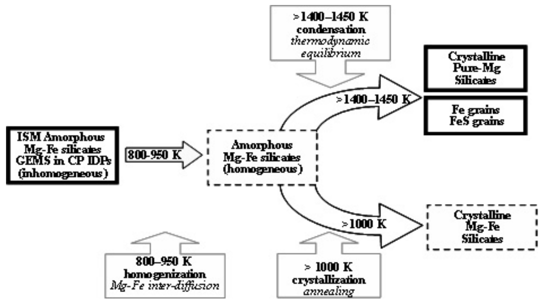
Crystalline Silicates in Comets are from the Solar Nebula



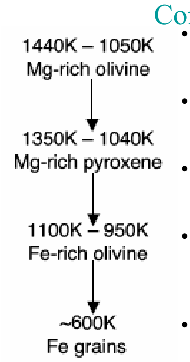
PPD Evolution: Crystal Formation Mechanisms

- **Fe bearing amorphous silicates must be converted into Mg-rich crystals**
  1. Vaporization then condensation of Mg-rich crystal
  2. Condensation and growth of Mg-rich amorphous silicates, followed by crystallization (through annealing)
  3. Reduction of Fe-rich silicates (e.g., by C) producing Mg-rich amorphous silicates followed by crystallization
  4. Reduction of Fe-rich silicates post-crystallization (with 100% efficiency)

Equilibrium (+ Radial Diffusion)



Condensation Mechanism



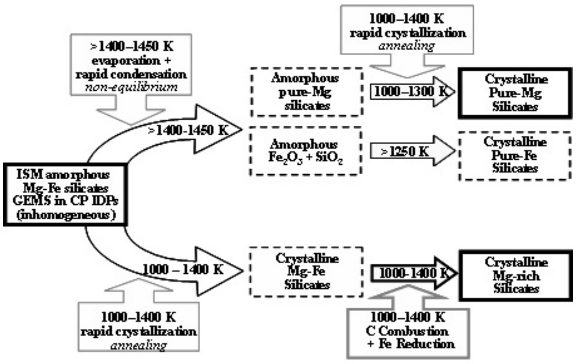
Grossman 1972; Tielens 1998

- In high vapor saturation conditions atoms, ions and molecules begin nucleation into clusters (Colangeli et al. 2003).
- Rapid growth (= fast cooling) of the clusters produces disordered (amorphous) particles (Nuth et al. 2002; Reitmeijer et al. 2002).
- Given time (= slow cooling), the cluster can rearrange to form ordered, crystalline structures (Colangeli et al. 2003).
- Crystalline grains are produced in the midplane of the inner disk (< 1 AU) where temperatures and pressures are conducive for condensation to occur
- Outward transport can populate comet forming zones (> 5 – 10 AU) with crystals.

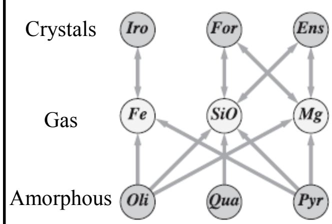
Annealing Mechanisms

- Accretion heating (< 2 AU for 10^{-7} $M_{\odot}$ yr^{-1})
- **Transient mechanisms** can act over larger volume of the disk.
- Shocks
  - Gravitational instabilities in ~10 AU region (Harker & Desch 2002)
  - X-Ray Flares R< 80AU (poster by Nakamoto & Miura)
- Annealing of Mg-pure amorphous grains produces Mg-pure crystalline grains (Brucato et al. 2002; Fabian et al. 2000)
- Rapid annealing of Fe-pure amorphous grains produces Fe-pure crystalline grains (not seen in comets or CP IDPs)
- Annealing of Fe containing GEMS produces moderately Fe-rich olivine crystals (Brownlee et al. 2005) (not seen in comets or CP IDPs)

Transient Heating

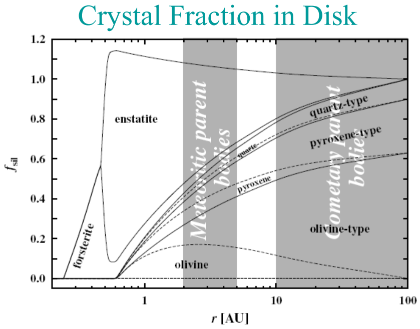


Mechanism for creating Mg-rich Crystals



- Annealing-sublimation-condensation sequence. The middle row refers to the vapor species. Solids are in the upper and lower rows (Gail 2004).
- Sublimation-Condensation produces Fe grains and Mg-rich crystals
- Therefore: **If Mg-rich crystals are formed through annealing, the Fe must diffuse out of the grain**
- Possible when annealed grain has C; similar to primitive enstatite chondrite formation conditions: C combusts to CO or CO2, removing O from the gas and lowering the oxygen fugacity, producing locally reducing conditions

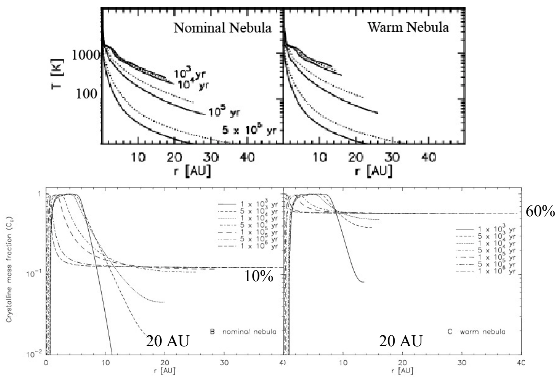
Crystal Fraction in Disk



Gail 2004

- Steady-state for accretion rate of 10^{-7} $M_\odot$ yr^{-1}
- Leads to crystal gradient
- Radial transport?

Early Delivery of Crystals to Outer Regions



Bockelee-Morvan et al. 2002

Summary/Future Directions

- Comets provide constraints on PPD models through the cross investigation of crystalline silicates
- Mg-rich crystals are evidence for thermal processing in PPDs (condensation and possible annealing of ISM grains)
- Annealing in shocks requires that Fe diffuses out of amorphous silicates, facilitated by C in the grains
- A lot of interstellar organics and ices survive: not all of disk could have been heated, passed through inner hot region, or shocked
  - Mixture of hot and cold materials on submicron scales implies large scale radial mixing prior to grain aggregation and subsequent cometesimal formation
  - OR an inefficient annealing process acting at large disk radii
  - WARNING: in situ aqueous alteration of silicates from olivines & pyroxenes to layer lattice silicates could occur in shocks beyond the snow line (Fred Ciesla’s shock models) AND layer lattice silicates absent in comets

Summary/Future Directions

- More comets need to be observed (JF & OC comets with Spitzer, VISIR, TIMMI2)
  - Parent body processing and grain “weathering”
- More modeling of disk processes: cause of turbulent diffusion and characterization of shocks
- Link radial-dependent mineral gradients with PPD opacities and disk geometries (inner disk walls, changes in scale height)