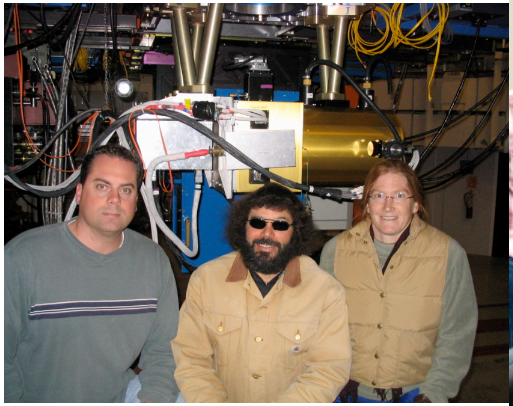
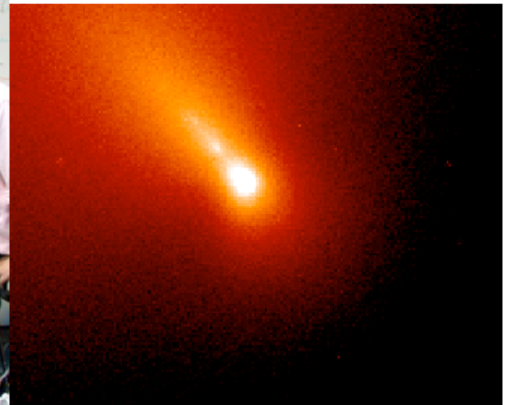
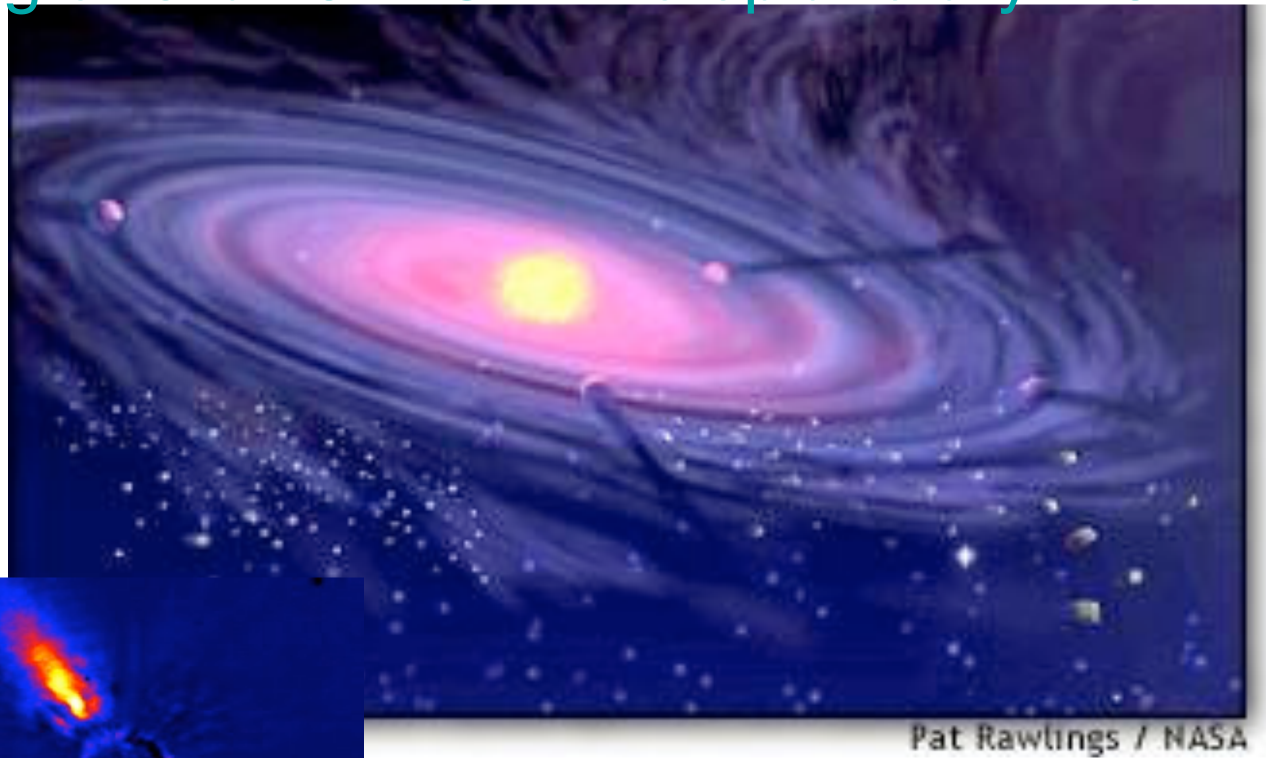
IR Observations and Mineralogy of Comet Dust Grains

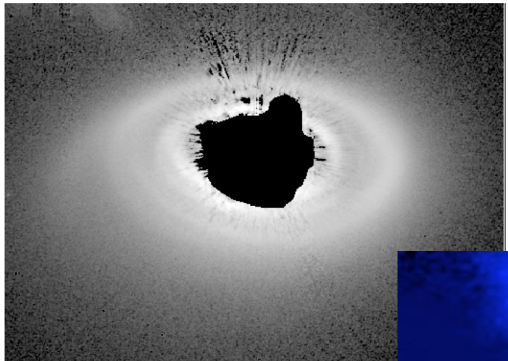
Diane H. Wooden
NASA Ames Research Center
with co-Is David E. Harker (UCSD) & Chick Woodward (U. Minn.)
& Deep Impact: Sugita and collaborators

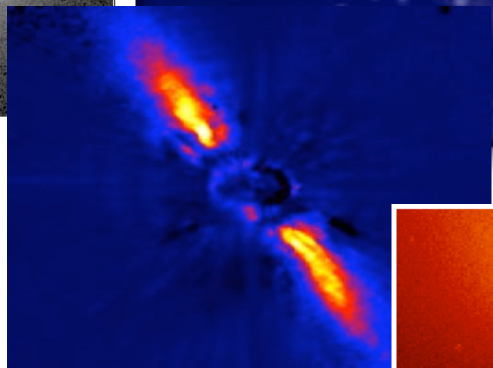


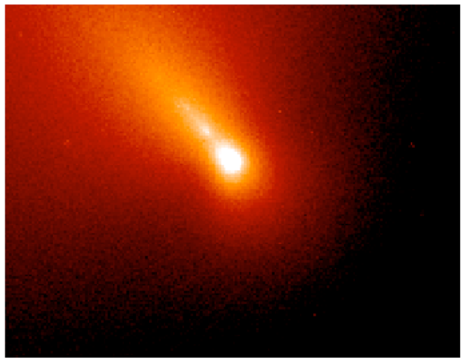


I. Motivation: Comets Probe the Effects of Heating and Radial Mixing of Grains in Our Protoplanetary Disk

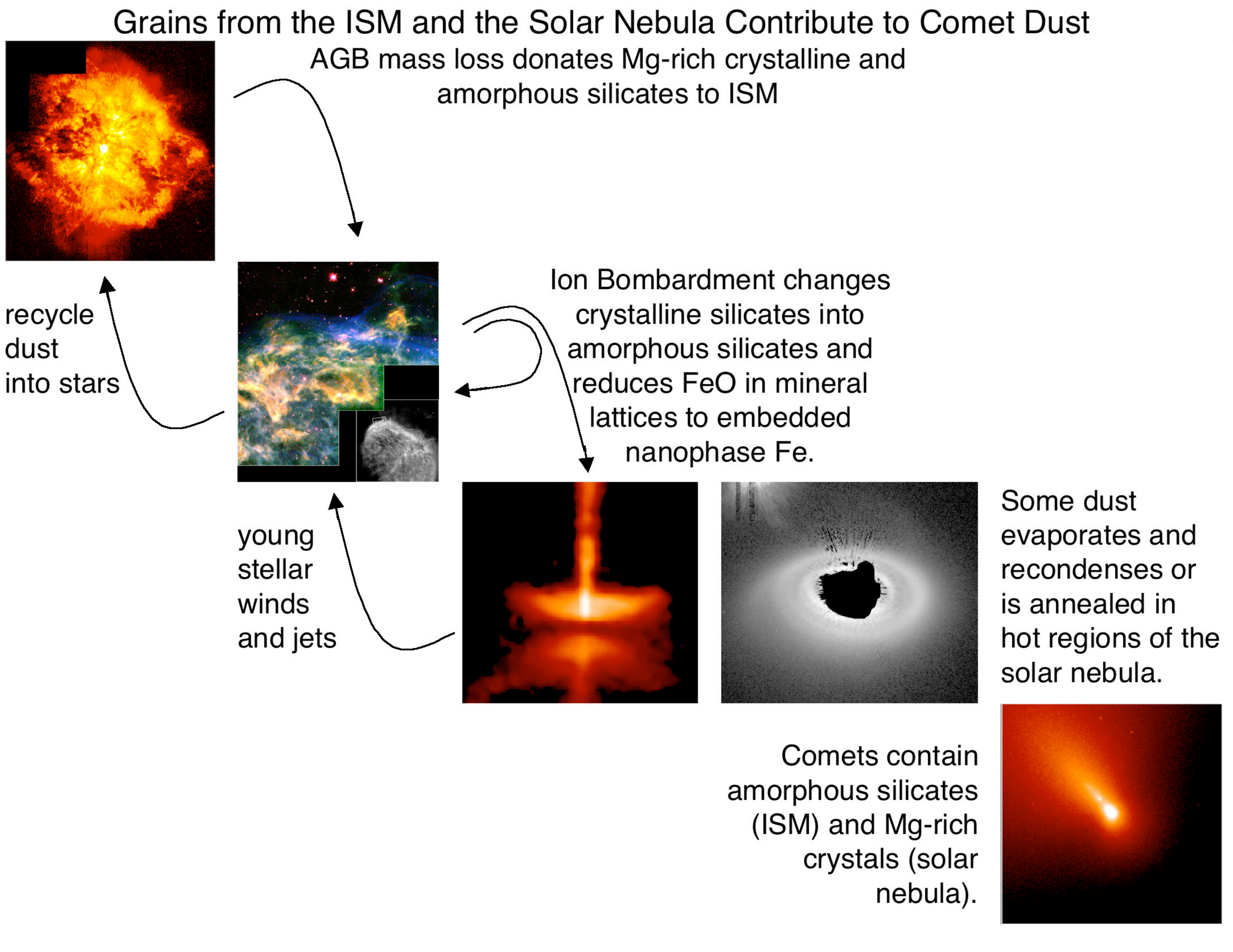






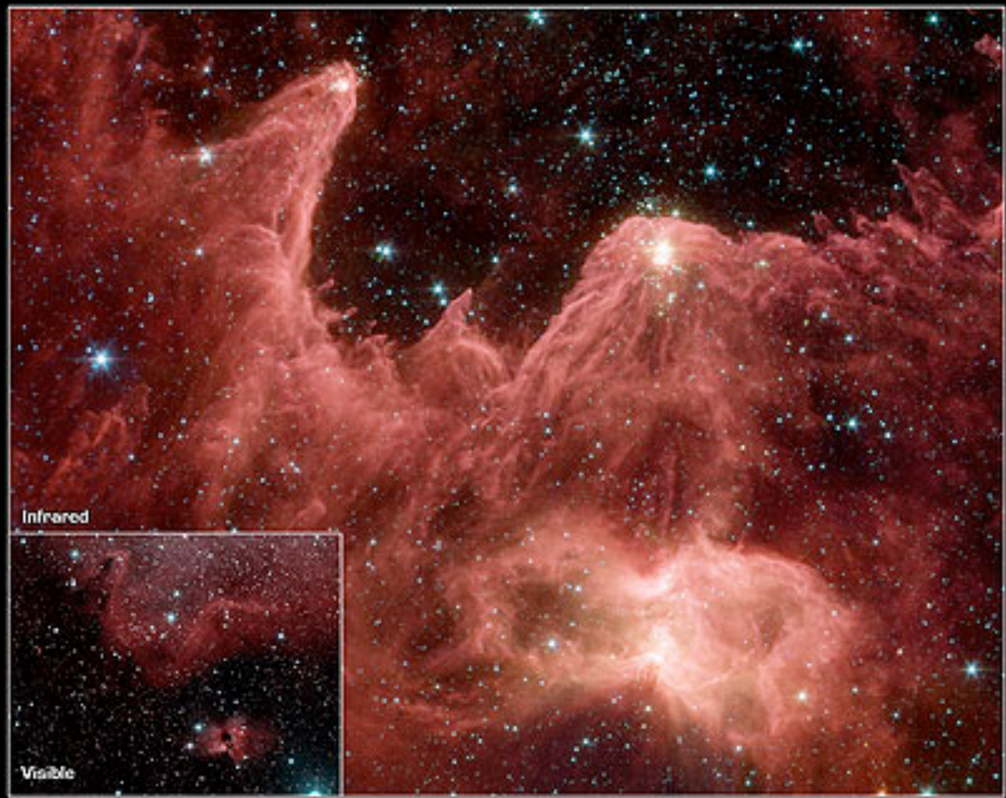


Comet grains constrain interstellar and solar nebula processes



proto-
stars:
white
yellow

3.6 μm
4.5 μm
5.8 μm
8.0 μm

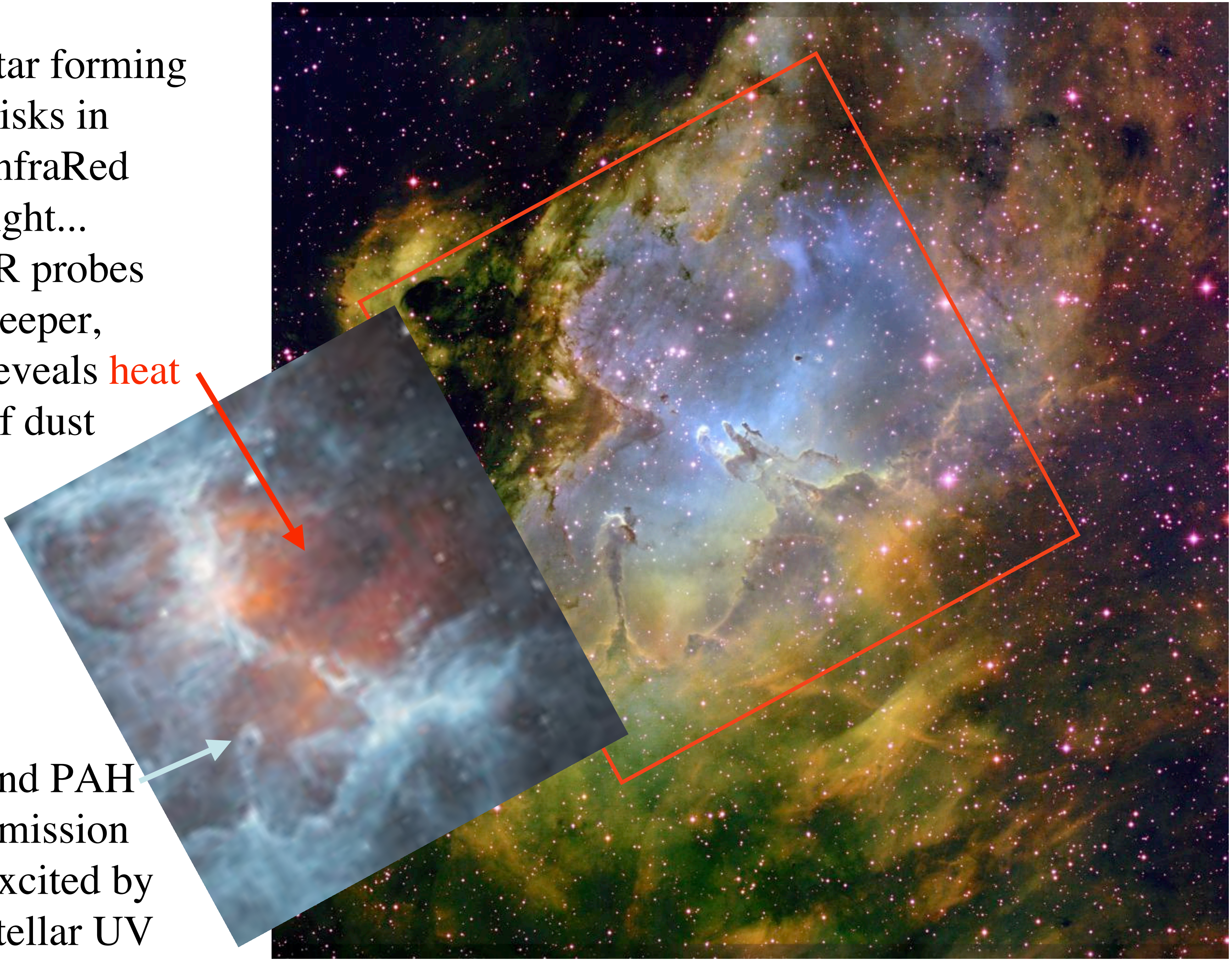


"Mountains of Creation" in W5 Star-Forming Region

Spitzer Space Telescope • IRAC
Visible: DSS
ssc2005-23a

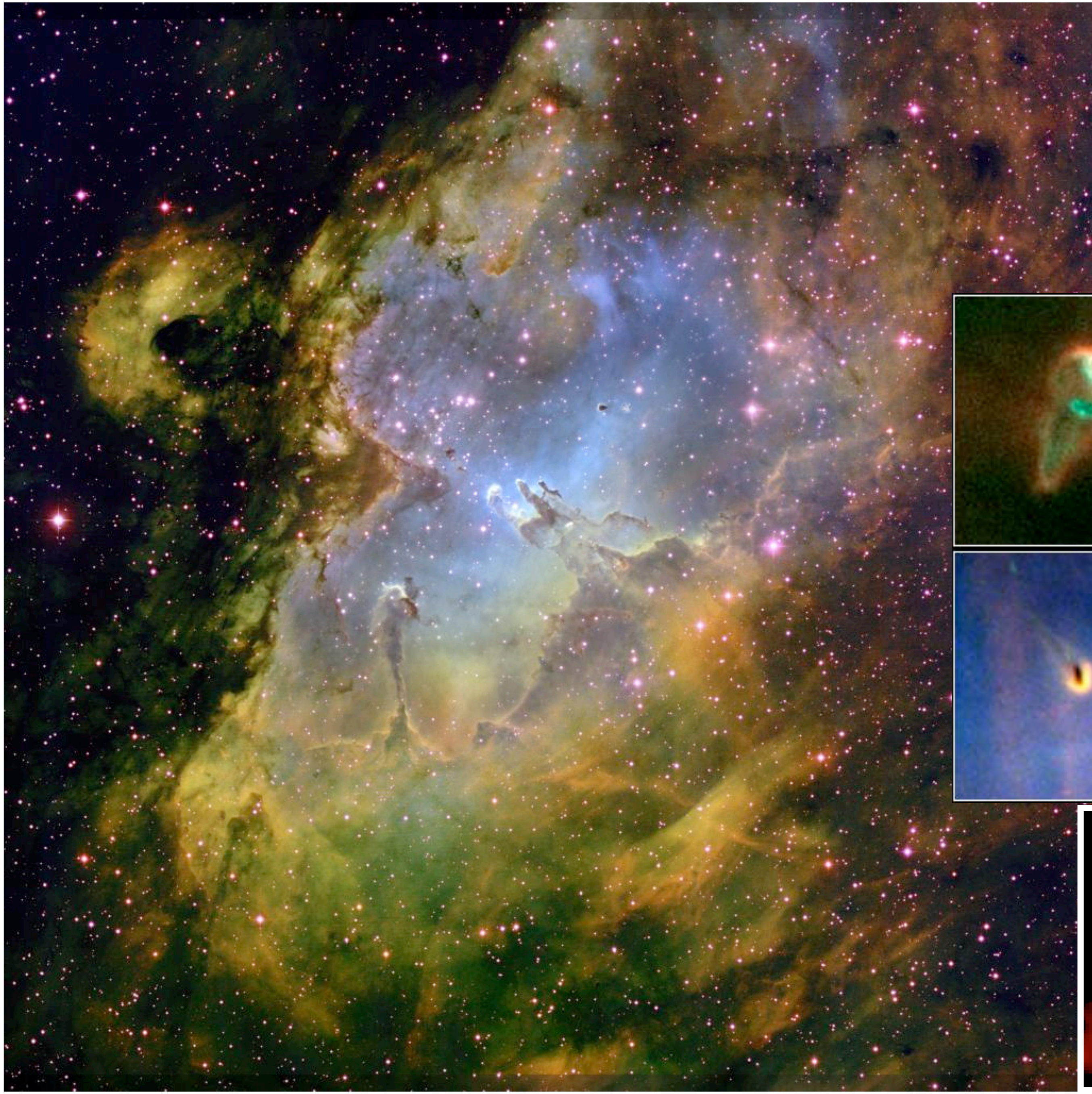
NASA / JPL-Caltech / L. Allen (Harvard-Smithsonian CfA)

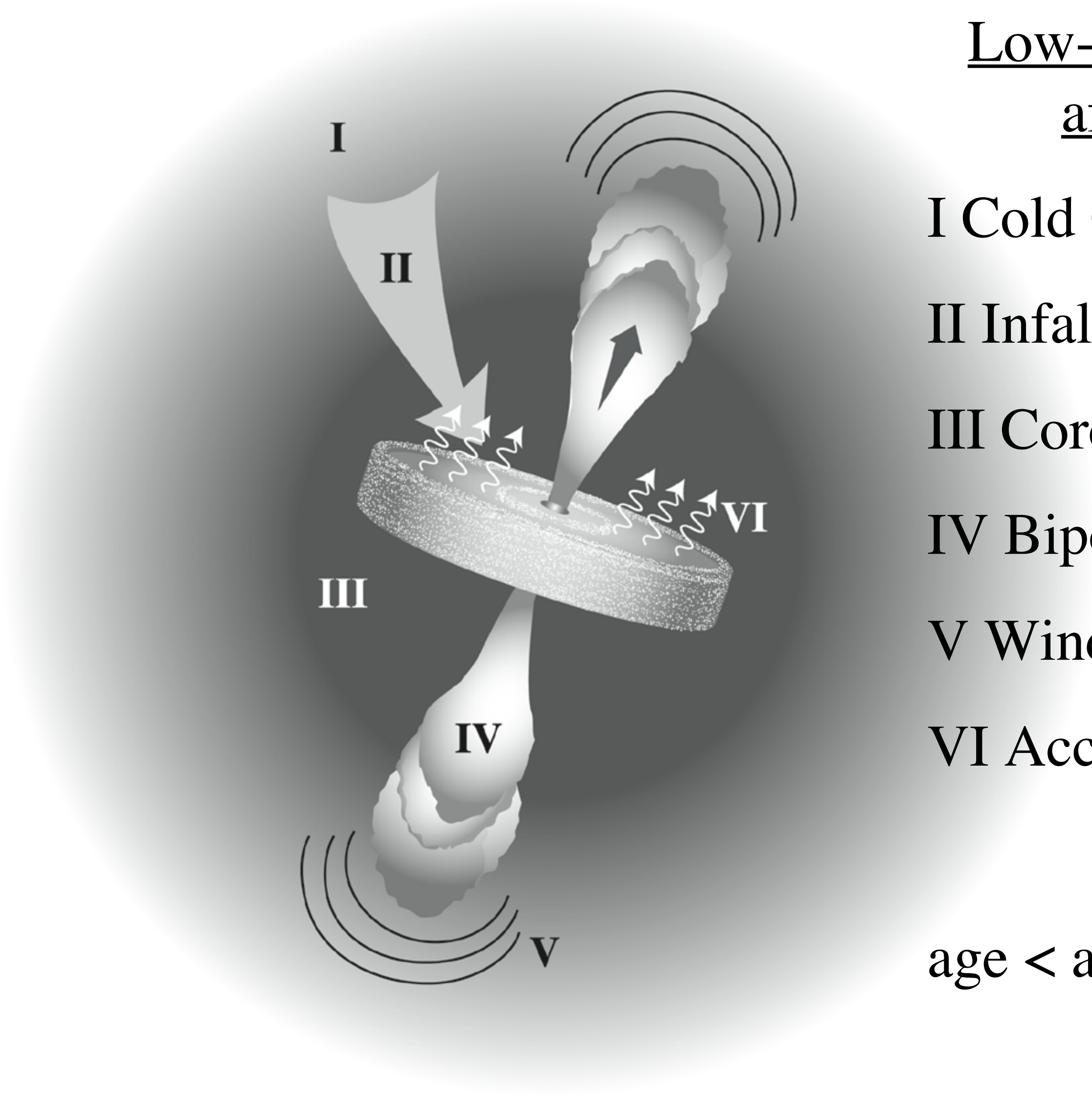
star forming disks in InfraRed light...
IR probes deeper, reveals heat of dust



and PAH emission excited by stellar UV

star-forming disks
in visible light
-- emitted
& scattered





Low-mass ProtoPlanetary Disk affects its Environment

I Cold Cloud with warm Core

II Infall

III Core warmed by star+disk

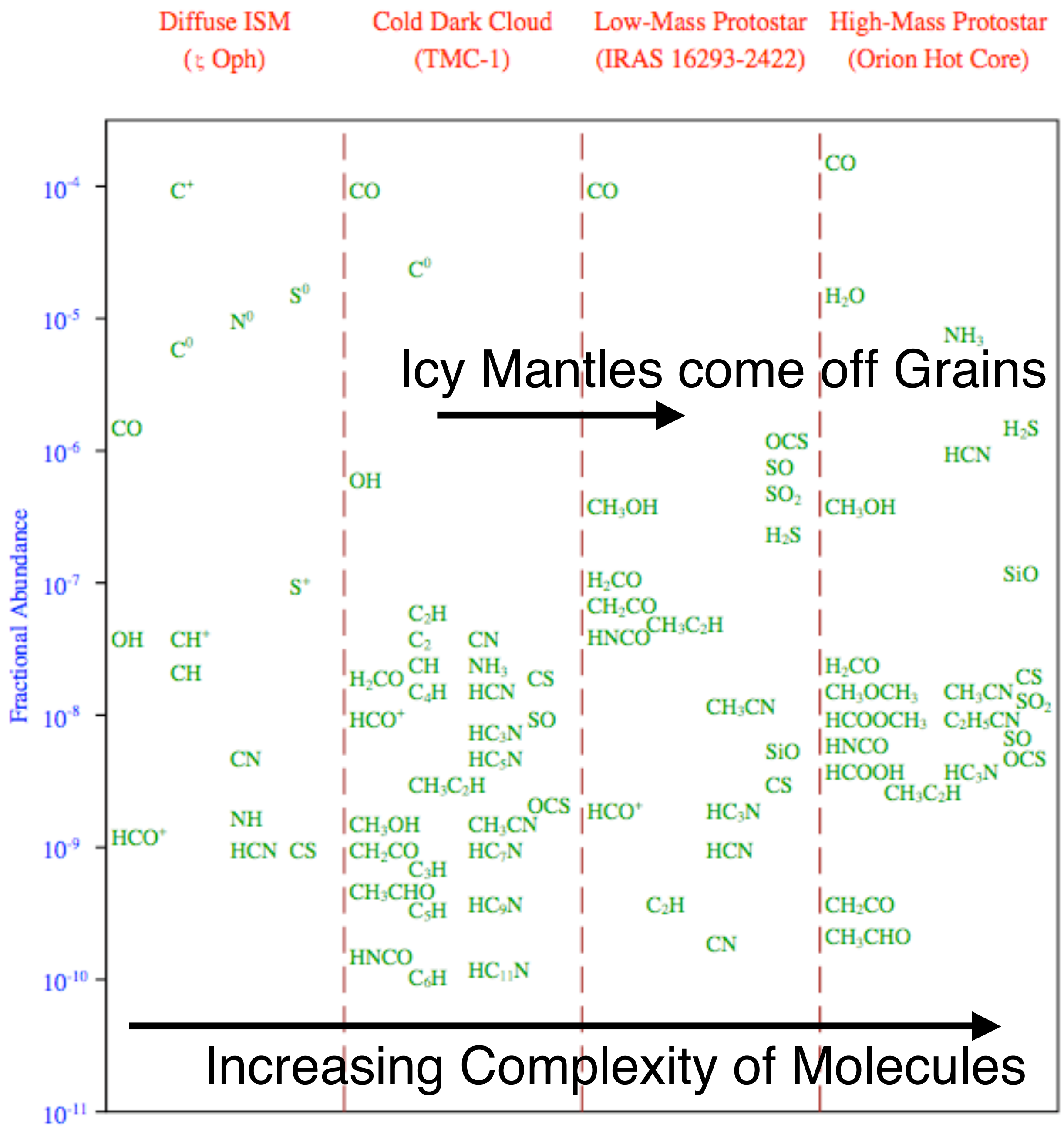
IV Bipolar Outflow

V Wind-cloud Bow Shock

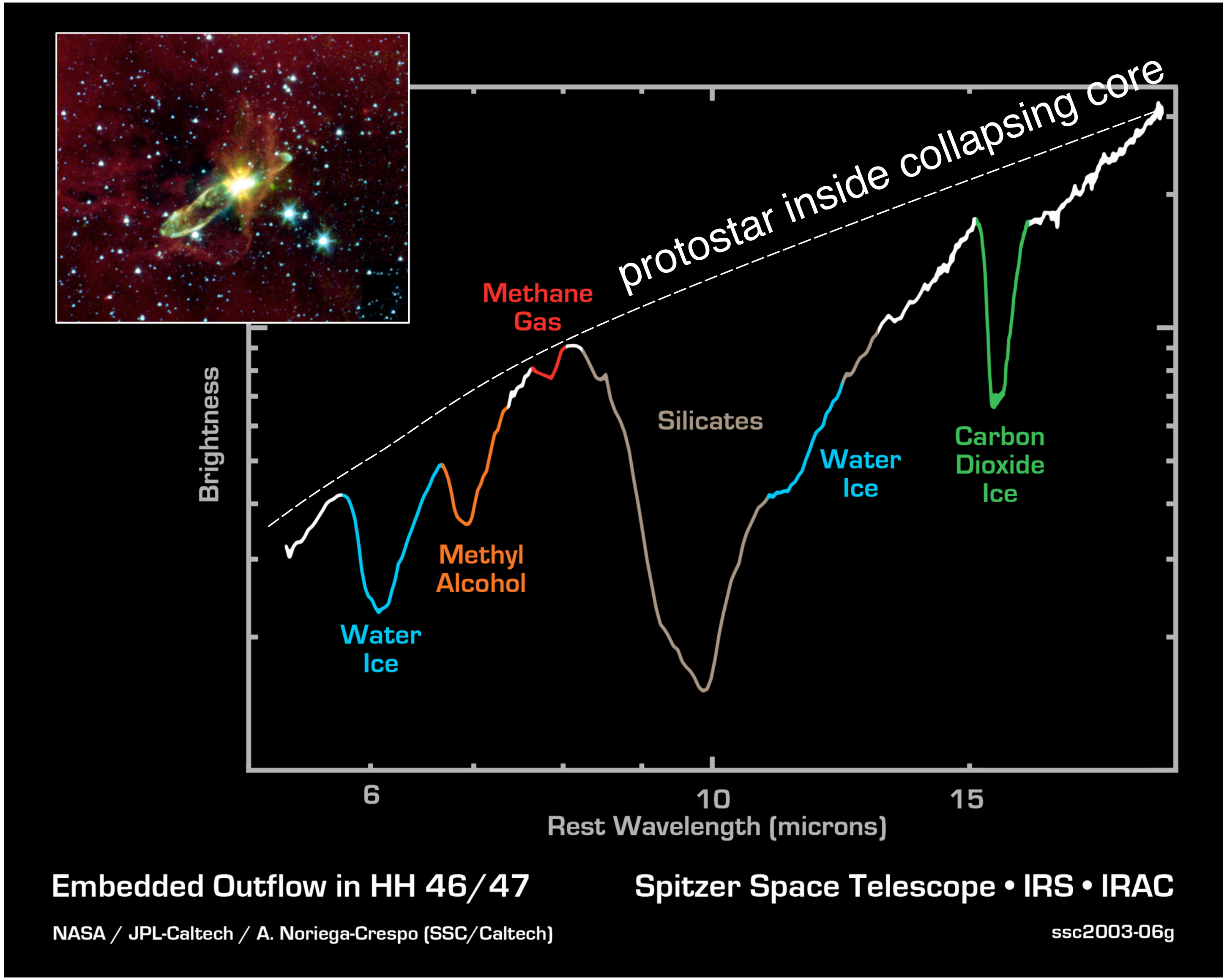
VI Accretion shock at disk surface

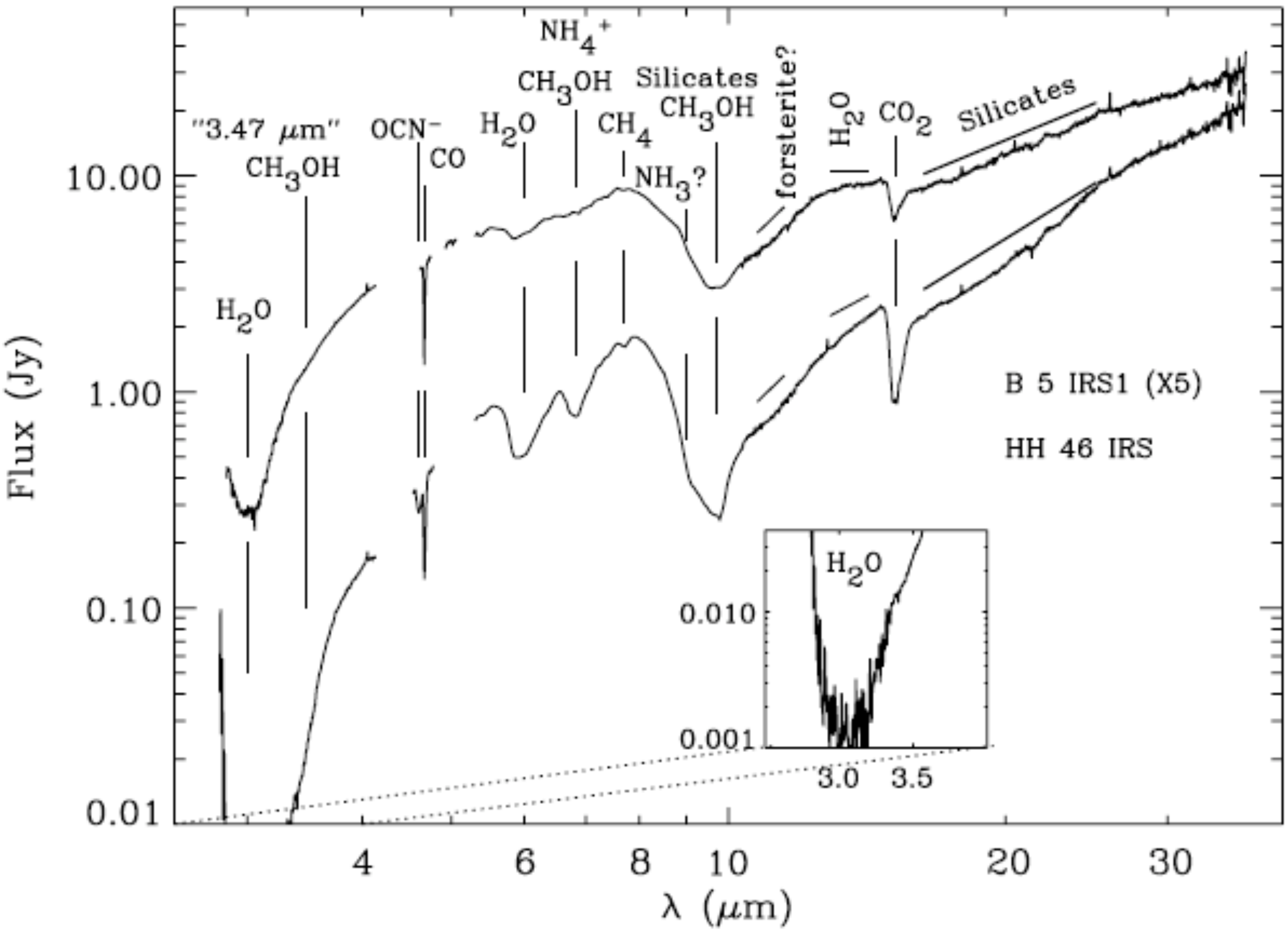
age < about 100,000 yr

Wooden et al. Comets II

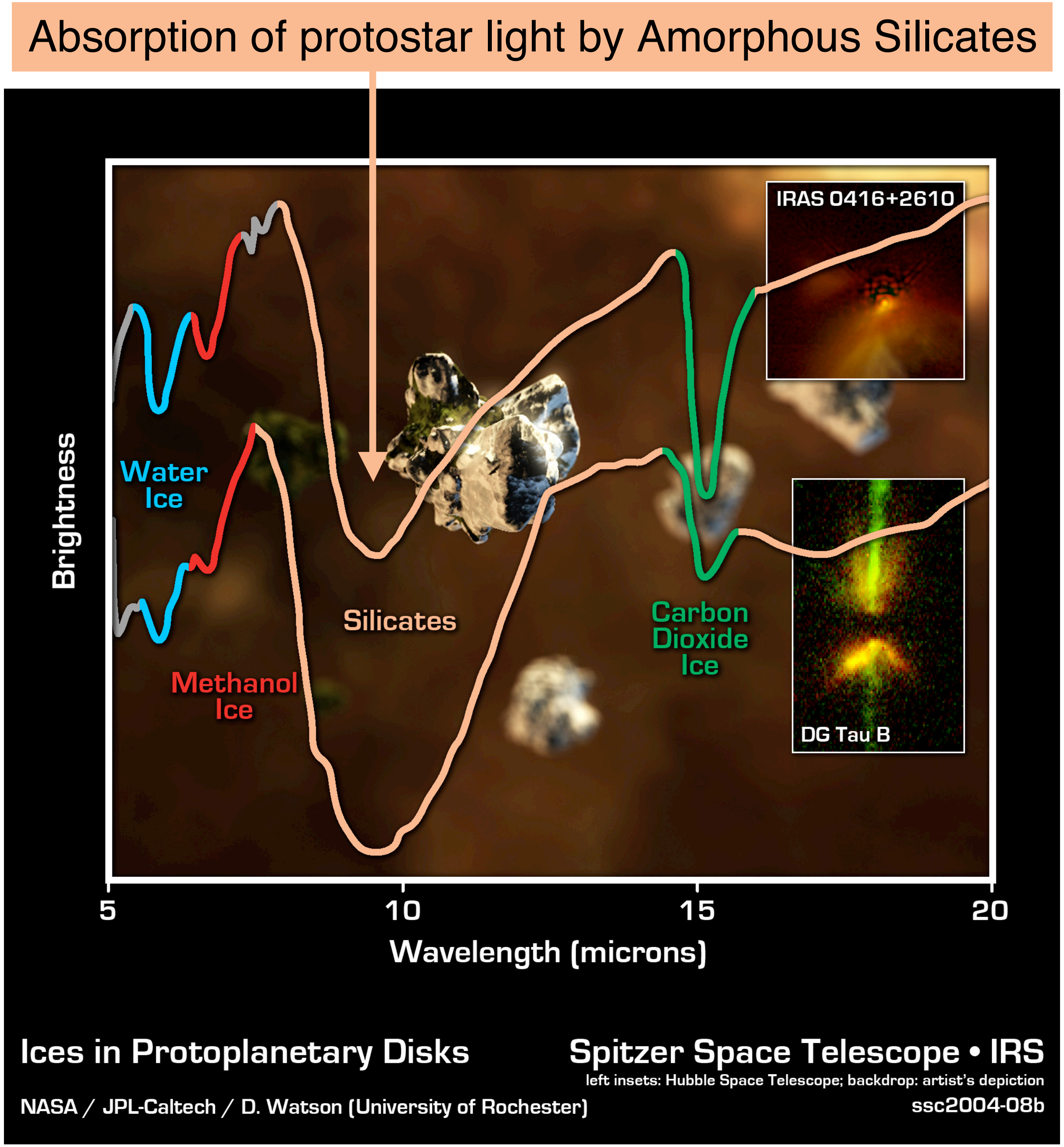


Wooden et al. Comets II

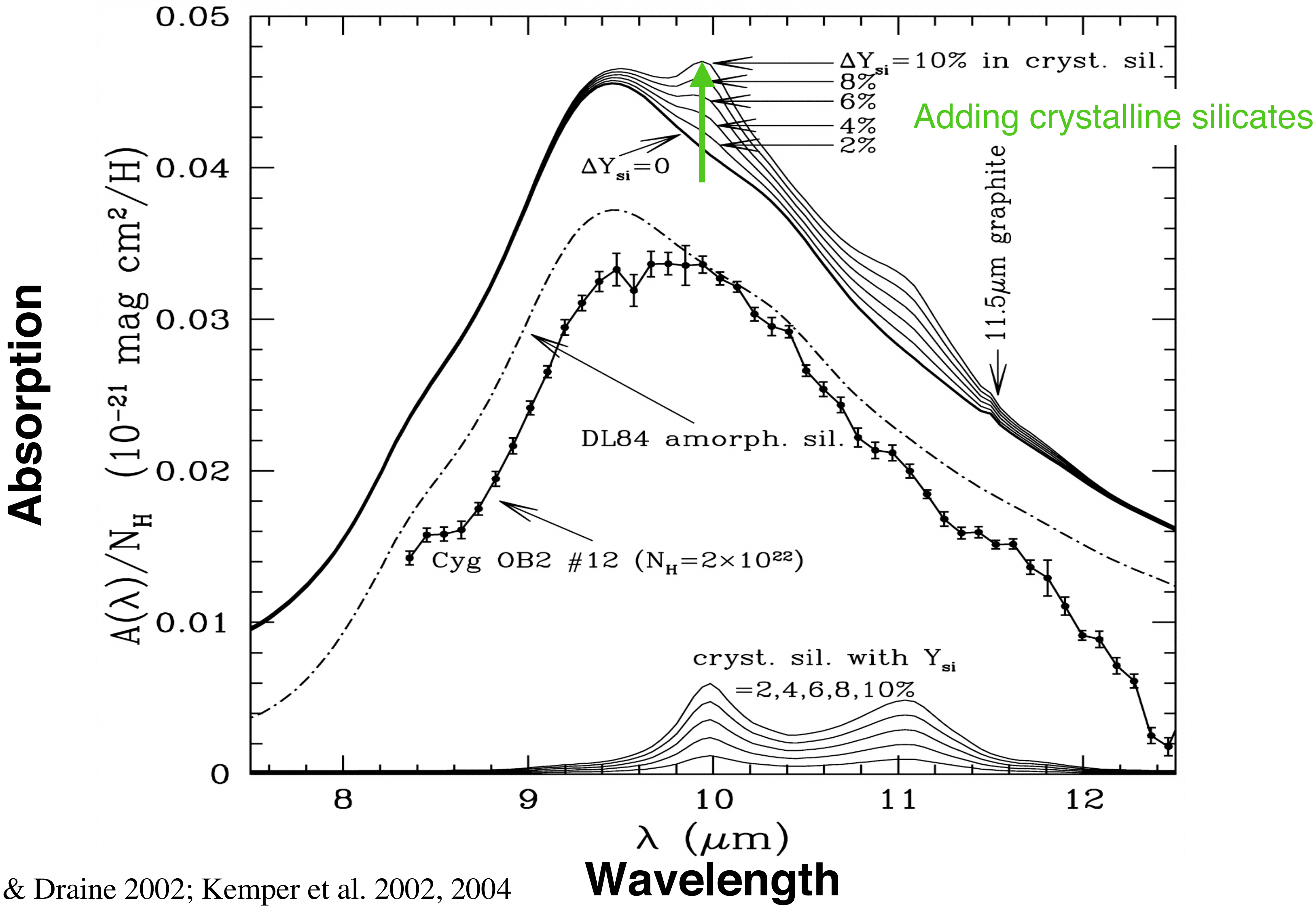

protostar inside collapsing core
Methane Gas
Methyl Alcohol
Water Ice
Silicates
Water Ice
Carbon Dioxide Ice
Brightness
6
10
15
Rest Wavelength (microns)
Embedded Outflow in HH 46/47
Spitzer Space Telescope • IRS • IRAC
NASA / JPL-Caltech / A. Noriega-Crespo (SSC/Caltech)
ssc2003-06g



Boogert et al. 2004 ApJS 154: 359-362

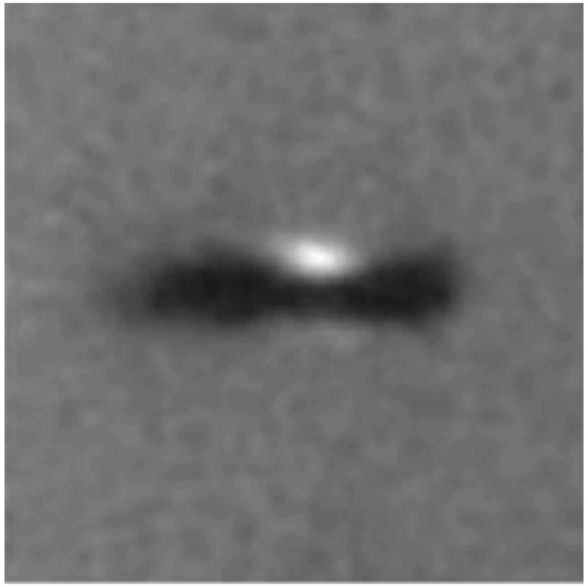

Absorption of protostar light by Amorphous Silicates
IRAS 0416+2610
Water
Ice
Methanol
Ice
Silicates
Carbon
Dioxide
Ice
DG Tau B
Brightness
5
10
15
20
Wavelength (microns)
Ices in Protoplanetary Disks
Spitzer Space Telescope • IRS
left insets: Hubble Space Telescope; backdrop: artist's depiction
NASA / JPL-Caltech / D. Watson (University of Rochester)
ssc2004-08b

Absorption Spectra through ISM Lines of Sight Show ISM Crystalline Silicates are Rare (<1–5%)



Li & Draine 2002; Kemper et al. 2002, 2004

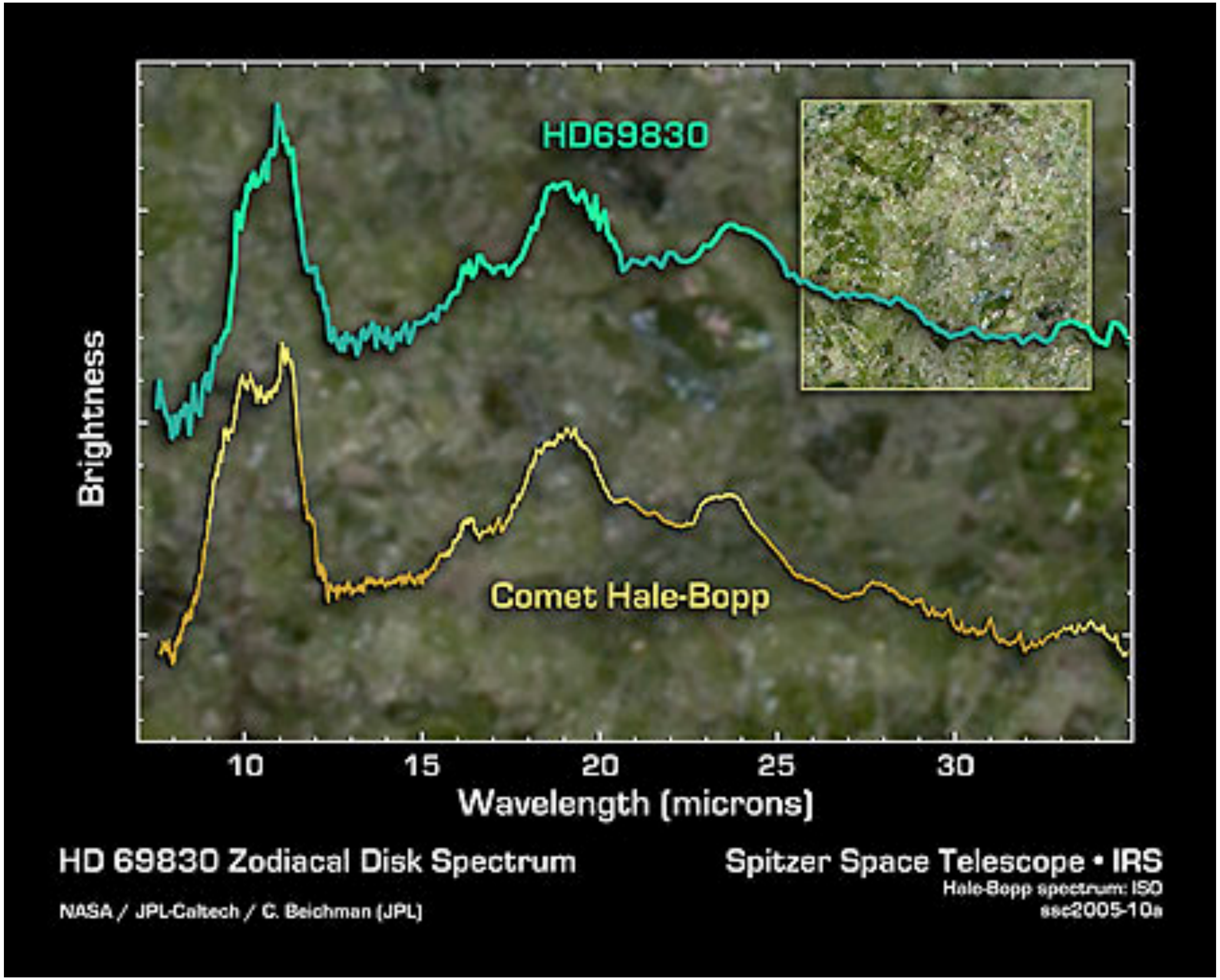
The Mineralogy of Silicate Dust Changes from Amorphous to Crystalline from Protostar Embedded within Core (Class 0 Young Stellar Object) to Exposed Protoplanetary Disk (Class 2 Young Stellar Object)



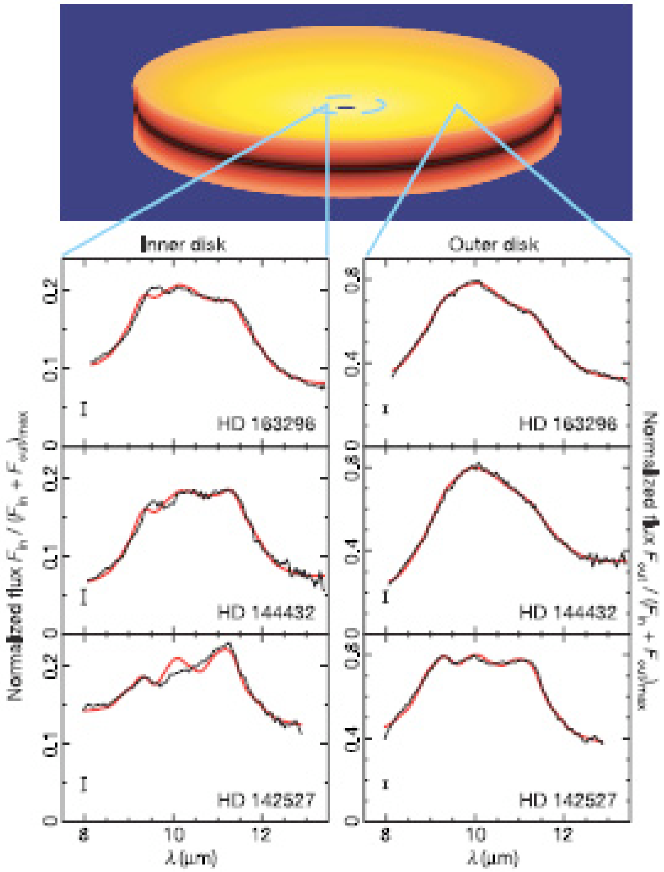
HST Image of Protoplanetary Disk in Orion Nebula

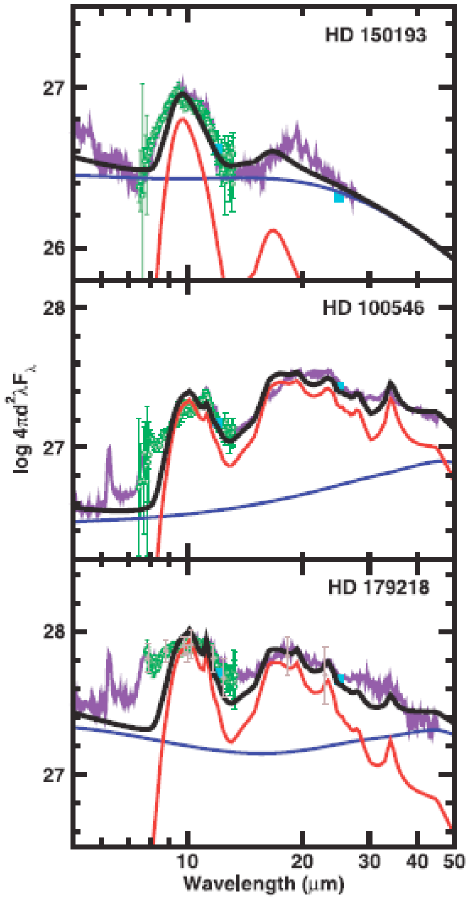
Flared Proto-Planetary Disc
(Artist's Impression)

ESO Press Photo 36/06 (28 September 2006)


HD69830
Comet Hale-Bopp
Brightness
10
15
20
25
30
Wavelength (microns)
HD 69830 Zodiacal Disk Spectrum
Spitzer Space Telescope • IRS
Hale-Bopp spectrum: ISO
ssc2005-10a
NASA / JPL-Caltech / C. Beichman (JPL)

Crystal Enhancements in Inner Regions of PPDs



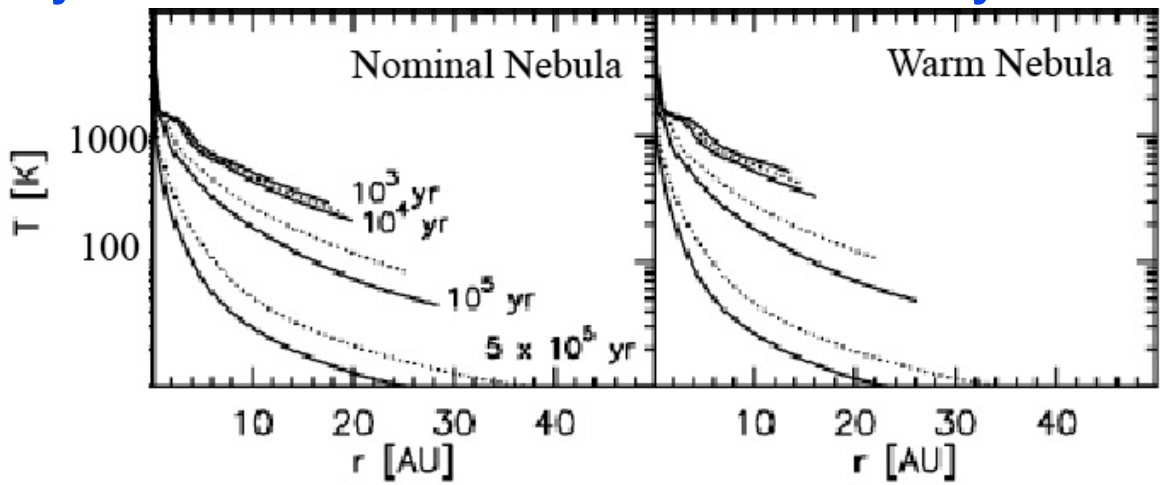


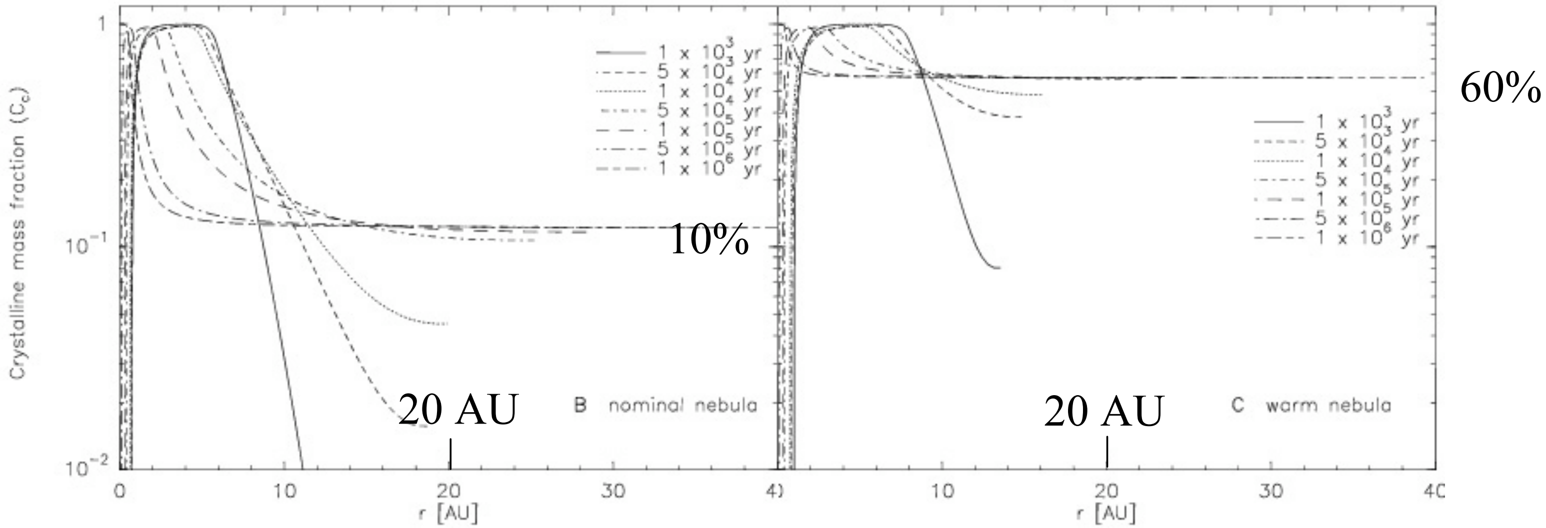
Inner Disk compared to whole disk:
2-6 times more crystals at < 2 AU
VLT+MIDI Interferometry
van Boekel et al. (2004)

Inner Disk compared to outer disk:
2-6 times more crystals at < 5 AU
ISO+HIFOGS **S**pectral **E**nergy **D**istr.s
Harker, Wooden et al. (2005)

Scenario1: Early Delivery of Crystals to Outer Disk

Warm nebula model: Crystalline Fraction at r>20 AU at Time > 5 10^4 yr
Uniform Crystalline Fraction at r>2 AU at Time >5 10^5 yr





Bockelee-Morvan et al. 2002; similar concepts Dullemond et al. 2006, f_{cryst}~ ang. momentum

Initial ProtoPlanetary Disk Composition
= ISM and molecular cloud core

•RARE Crystalline Silicates

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

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

•Abundant Mg-Fe Amorphous Silicates

mostly Olivine and some Pyroxene towards Galactic Center (Kemper et al. 2005)

ISM absorption spectrum matches comets and an ensemble of GEMS from anhydrous Chondritic Porous Interplanetary Dust Particles of probable cometary origin

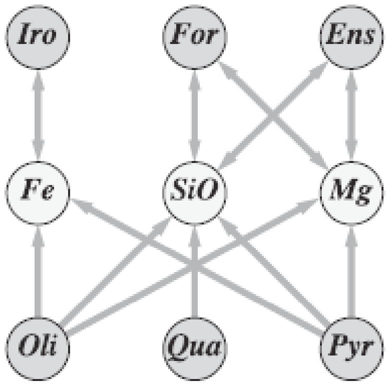
Fe is in the Silicate Dust in Galactic-Disk Clouds, as shown by ISM Depletion Studies **[Jones, 2000,JGR]**

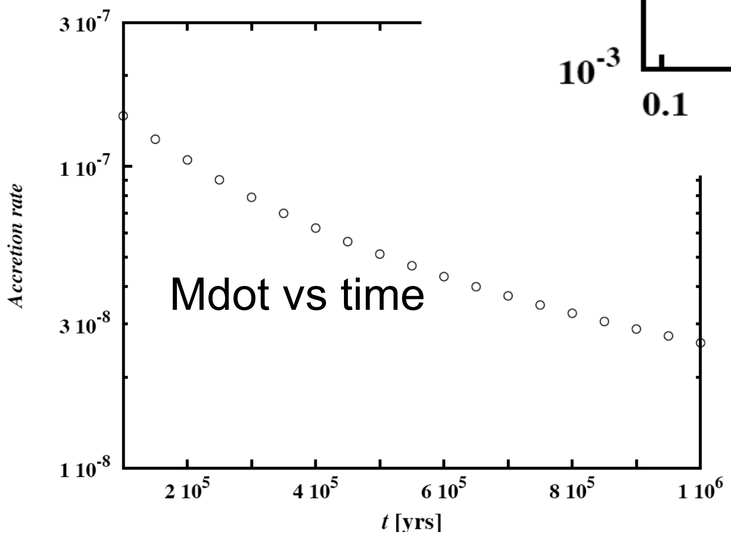
•**Abundant Carbon** in aromatic, aliphatic, 'amorphous' carbon bonds, also some C in SiC made by carbon stars, 10-15% in PAHs

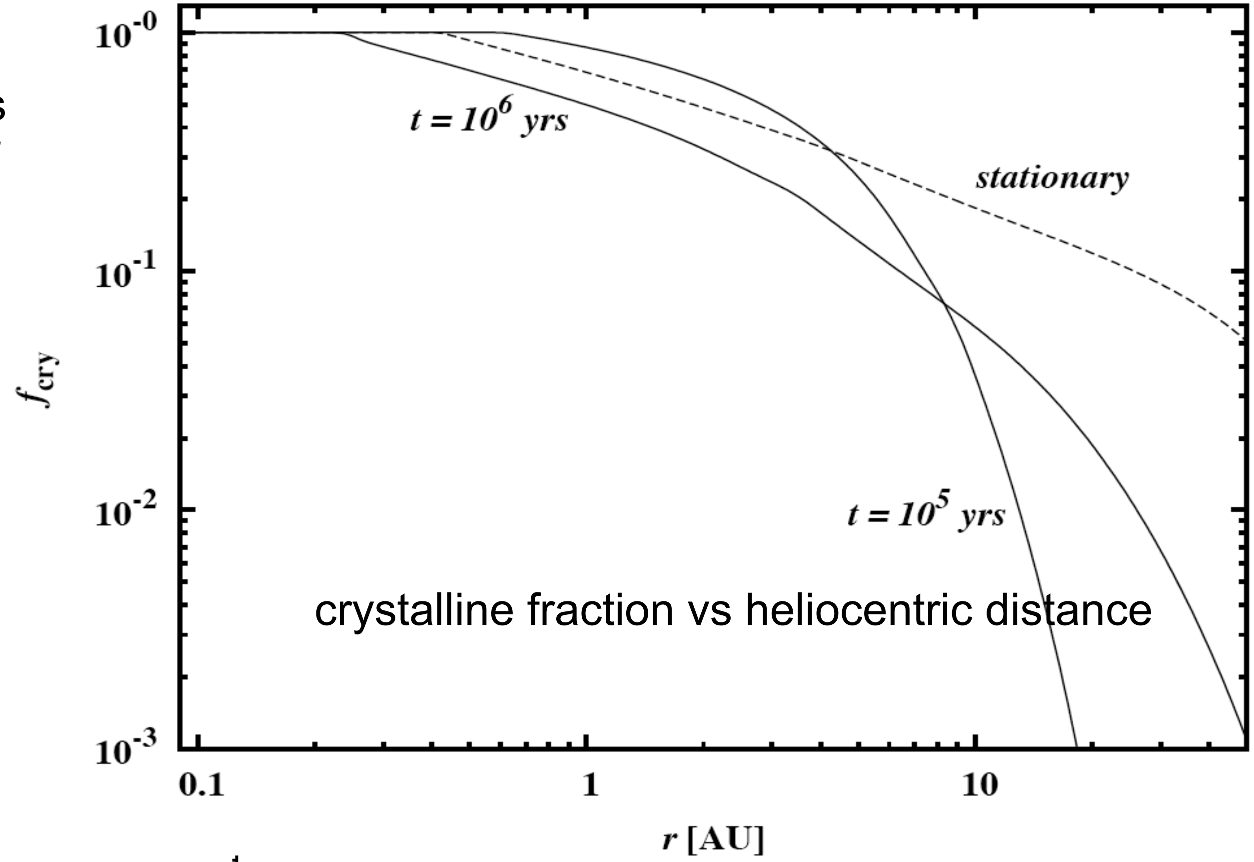
• organics & ices (often discussed by Charnley & Ehrenfreund)

Scenario2: Crystal Gradient Evolving still at 1Myr

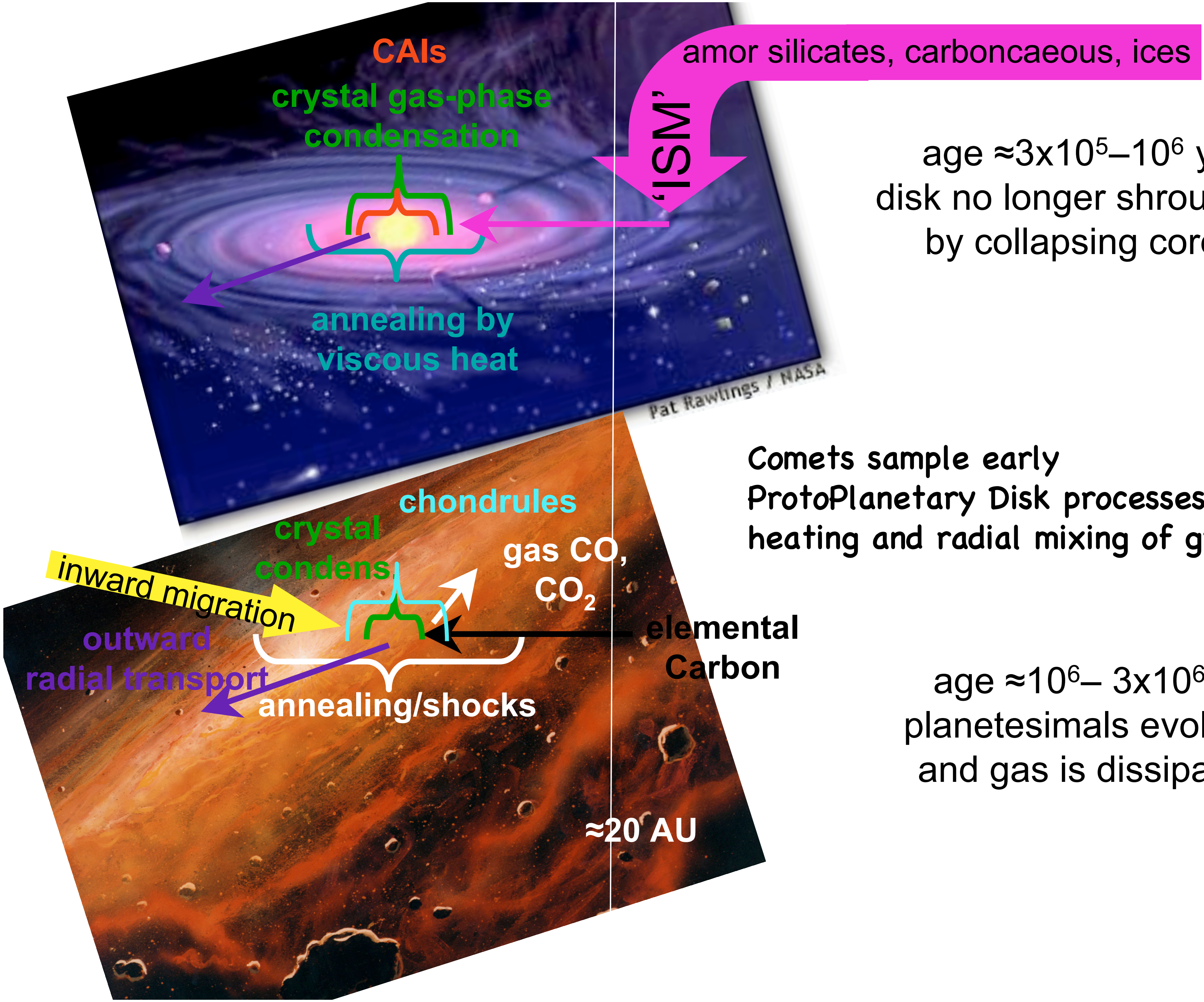
crystals condense and are annealed, includes grain-gas exchange of Fe







2-D, time-dependent model
Gail 2004, Wehrstedt & Gail 2006

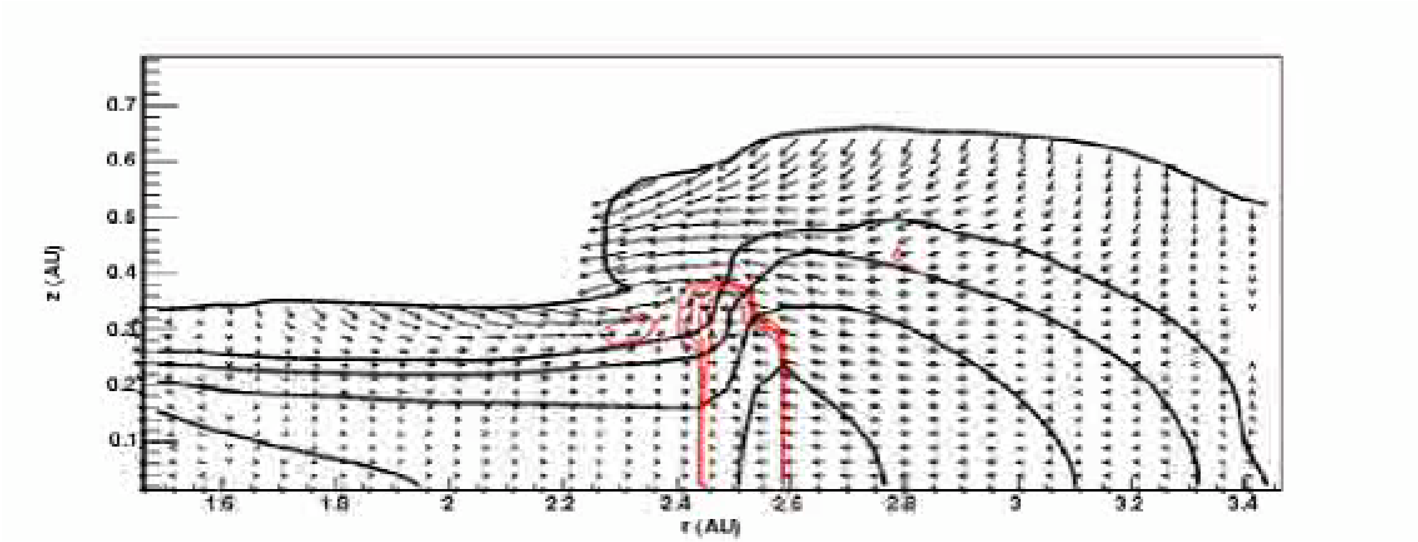


age ≈$3x10^5$–10^6 yr
disk no longer shrouded
by collapsing core

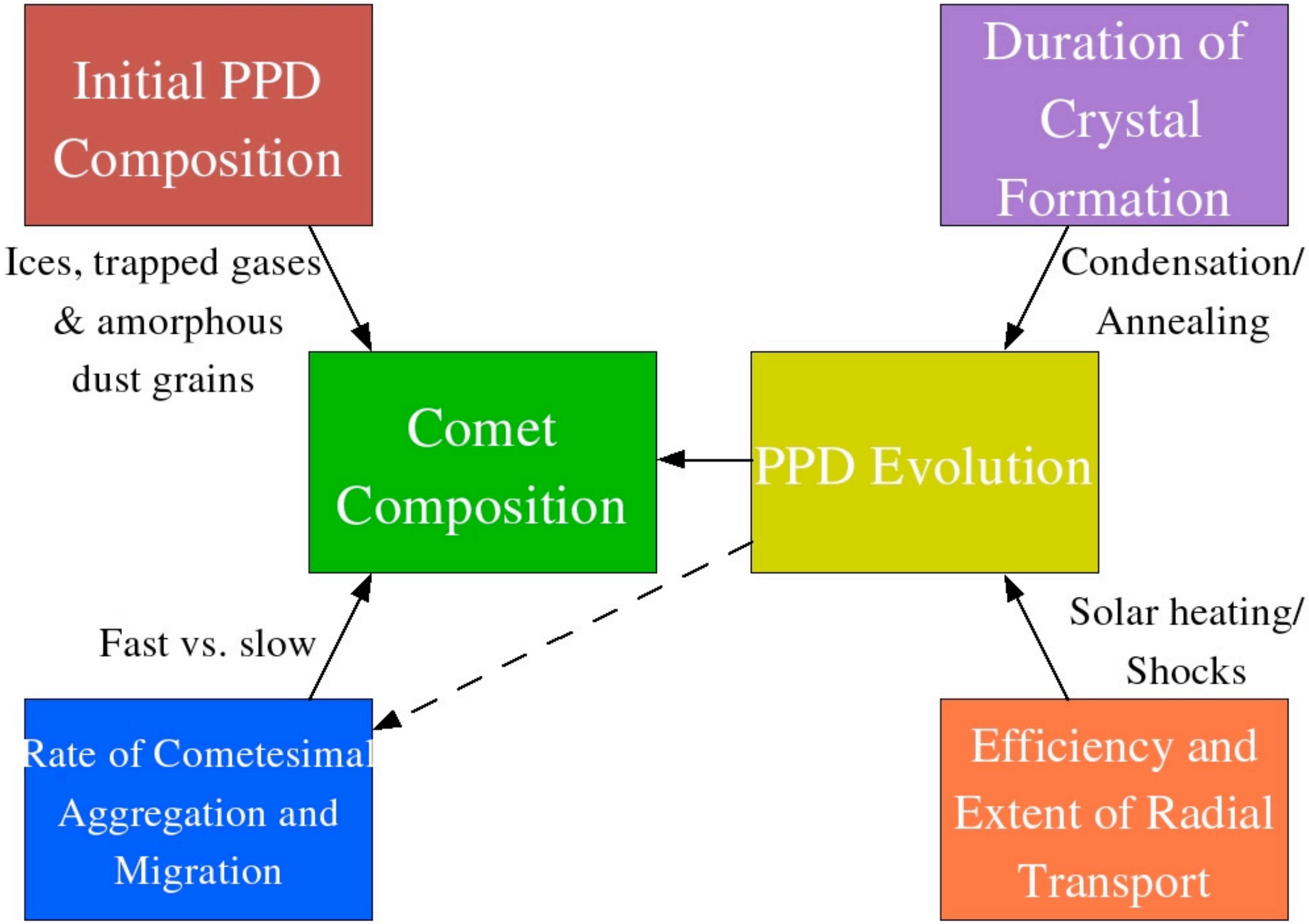
Comets sample early
ProtoPlanetary Disk processes:
heating and radial mixing of grains

age ≈10^6– $3x10^6$ yr
planetesimals evolving
and gas is dissipating

Durisen's crashing wave of gas in the solar nebula:
http://westworld.astro.indiana.edu/movies.html



What Determines Comet Composition?



Break after Part I

QUESTIONS from Students at Planetary School 2006, motivated by the Part I Introduction...

In small groups, students formulated questions about comets and the implications comet dust provide for processes in the protoplanetary disk. These questions were then answered using selected slides in the rest of this powerpoint presentation.

Silicate Mineralogy Questions

- Why does the silicate feature appear at 10μm?
- How can we distinguish between olivine and pyroxene in the amorphous silicate phase (in silicates that have amorphous or highly disordered structures)?
- Can we deny the existence of crystalline silicates?
- What is the difference between the constraints on the crystalline silicate fraction in the interstellar medium: "<2% towards the Galactic Center" compared to "<5% towards other lines-of-sight in the ISM"?

PPDisk Radial Transport Questions

- Only tiny particles can couple with the gas and diffuse outwards. Which process is dominant: collisional growth or collisional disruption?
- If outward radial mixing of dust transports only the smallest grains and grains are efficiently aggregating to larger sizes and settling to the disk mid-plane, then does the need to radially migrate out crystals imply that dust aggregates must be actively destroyed to maintain the small grain population?
- What is the origin of shocks in disks?
- What controls the outward transport of crystalline silicates?
- What are the transport mechanisms for the crystalline silicates from the inner disk radii to the outer disk radii?
- How can we test the hypothesis of radial mixing of crystalline silicates?

Comet Nuclei Formation Questions

- Where in the comet nucleus do we find the materials from different radial distances in the disk (cold materials, such as water with ortho/para ratios indicating T<35K from the outer disk and crystalline silicates from the hot inner disk)? In other words, if the comets were formed at 30 AU, the core of the comet nucleus should be dominated by amorphous silicates; if comet nuclei either migrated inwards or radial mixing moved high temperature crystals outwards over time (1 Myr), then nuclear layers accumulated later might be richer in crystalline silicates. Is there evidence for this?
- Do collisions and/or space weathering play a significant role in changing primordial comet composition?
- Do we know when the comets formed? Do the materials inside comets (amorphous silicate grains compared to crystalline silicate grains) have the same formation age?

Comets-PPDisk Questions

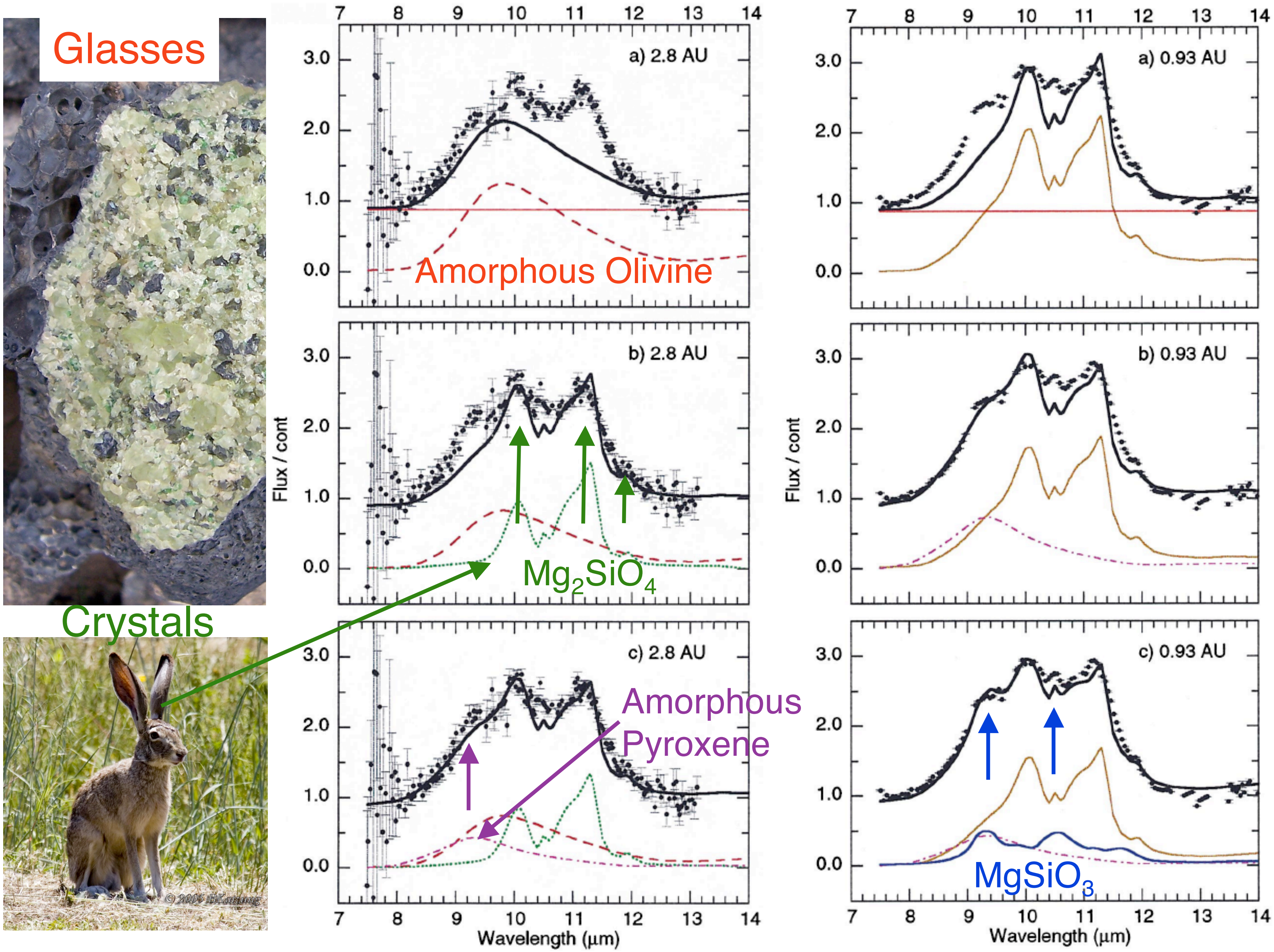
- Why do we think amorphous olivine and amorphous pyroxene constitute the initial protoplanetary disk (PPD) composition?
- Could the inner-disk silicate feature rich in crystalline silicates (MIDI observations, van Boekel) be an artifact of optical depth? If the silicates settle to the midplane, then do the observations of crystals only in inner disks imply that can see the midplane at small disk radii (<1–2 AU) but we cannot see the midplane at larger disk radii (>2 AU)?
- Currently, there is a discussion about crystalline versus amorphous minerals in the rocks (refractory minerals). Can future observations lead to a discussion about crystalline versus amorphous water ice and implications for formation and transport at different disk radii? What are the difficulties?

Answers to these questions primarily came from the following slides...

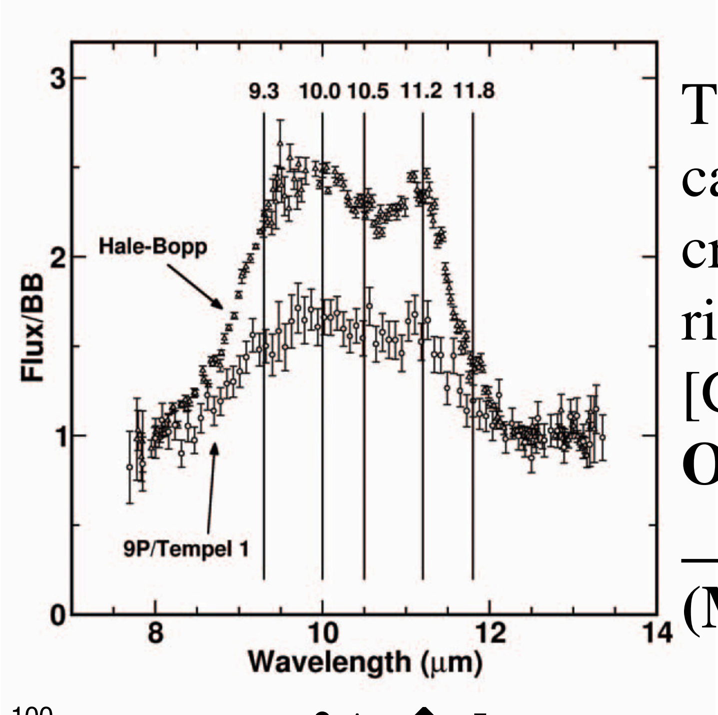
Part II. Silicate Mineralogy - Feature Identifications and Comet Modeling Techniques and Results... Deriving Grain Properties from IR Observations

Chart showing the computational steps in thermal emission models.

	Step 1	**Step 2**	**Step 3**	**Step 4**	**Step 5**
Computation Tools & Techniques	**Mie Scattering**	**Radiative Equilbrium**	**Solve Flux Integral**	**Sum the Fluxes**	**Minimize χ^2**
Inputs					
Minerals (Abbr.)	Opt.Const. & Radii $\{n, k\}, a$	Heliocentric Distance r_h	Size Distribution & Porosity $n(a), D$	Abundance Multipliers $N_{Mineral}$	Data SED
Outputs					
Amorphous Carbon (AC)	$Q_{\lambda, AC}(a)$	$T_{AC}(a, r_h)$	$F_{\lambda, AC}(a, r_h, n(a))$	Model SED $\Sigma\{N_{Mineral} * \lambda F_{\lambda, Mineral}\}$	Best Fit Model SED λF_λ
Amorphous Olivine (AO)	$Q_{\lambda, AO}(a)$	$T_{AO}(a, r_h)$	$F_{\lambda, AO}(a, r_h, n(a))$		
Amorphous Pyroxene (AP)	$Q_{\lambda, AP}(a)$	$T_{AP}(a, r_h)$	$F_{\lambda, AP}(a, r_h, n(a))$		
Crystalline Olivine (O)	$Q_{\lambda, O}(a)$	$T_O(a, r_h)$	$F_{\lambda, O}(a, r_h, n(a))$		
Crystalline Pyroxene (P)	$Q_{\lambda, P}(a)$	$T_P(a, r_h)$	$F_{\lambda, P}(a, r_h, n(a))$		



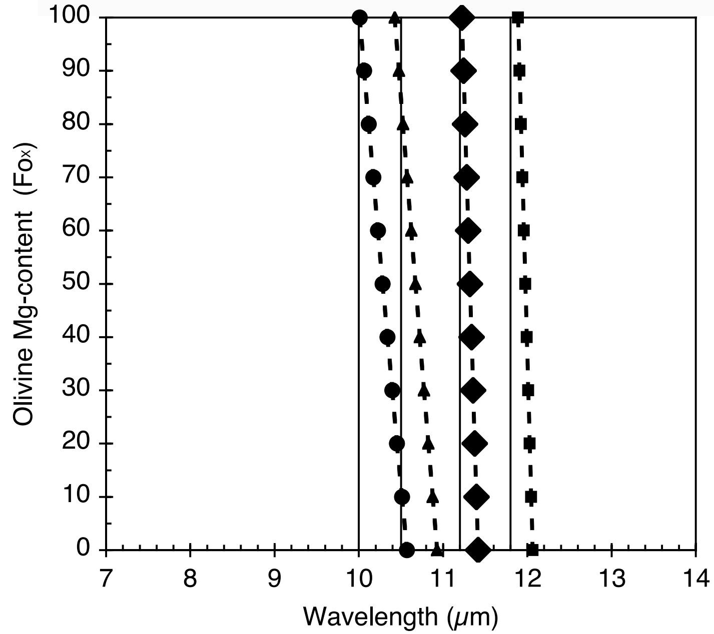
Glasses
Crystals
Amorphous Olivine
Mg_2SiO_4
Amorphous Pyroxene
$MgSiO_3$
a) 2.8 AU
b) 2.8 AU
c) 2.8 AU
a) 0.93 AU
b) 0.93 AU
c) 0.93 AU
Flux / cont
Wavelength (μm)

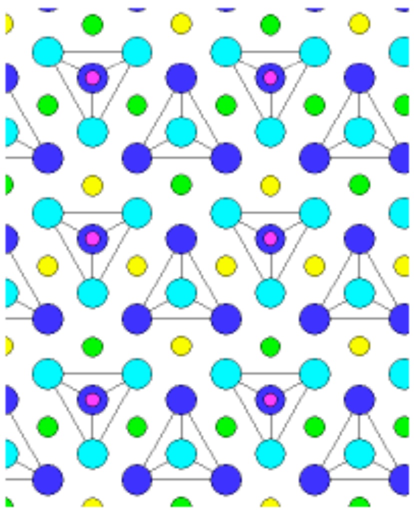


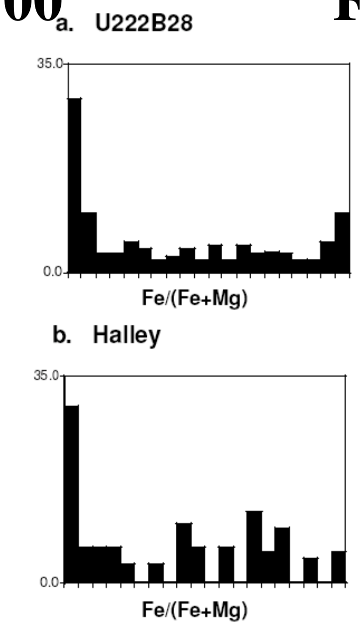
The wavelengths of the mid-IR features can show the Mg-content of mineral crystals: shorter wavelengths are Mg-rich, longer wavelengths are Fe-rich. [Chihara et al. 2003; Koike et al. 2002].

Olivine: Mg-content is

Mg / (Mg+Fe)	**= 1**	**0**
	Forsterite	**Fayalite**
	Fo 100	**Fo 0**







Scattering cross sections

The cross-sections for absorption, scattering, and extinction are expressions of the effective area of the interaction zone for a photon encounter with a particle.

These are often normalized to the geometric cross-sectional area of the particle.

Scattering Efficiencies

$$Q_{abs} = \frac{\pi a_{abs}^{\;2}}{\pi a^2} \qquad Q_{sca} = \frac{\pi a_{sca}^{\;2}}{\pi a^2} \qquad Q_{ext} = \frac{\pi a_{ext}^{\;2}}{\pi a^2}$$

extinction = absorption + scattering

$$\overline{Q} = \int_0^\infty \pi a^2 Q(a) N(a) da$$

For an emsemble of coma grains, the emissivity is weighted by the grain size distribution N(a).

Comet Comae Grains are in Radiative Equilibrium

• The IR-flux of dust particles at >~3 µm is dominated by re-radiation of the absorbed solar energy

• The radiated flux depends on nature and composition of the dust particles.

In thermal equilibrium the grain temperature is balanced by the absorbed flux in the UV and visible and the re-radiated thermal flux in the IR:

$$\int_0^\infty \frac{L_{\odot,\lambda}}{4\pi r^2} Q_{abs}(\lambda, a)\pi a^2 \, d\lambda = \int_0^\infty \pi B[\lambda, T(a,r)] Q_{abs}(\lambda, a) 4\pi a^2 \, d\lambda$$

absorbed flux (sunlight) — thermally emitted flux

To obtain the total emitted flux integrate over the size distribution of all grains:

$$F_\lambda = \int_{a_1}^{a_2} \pi B[\lambda, T(a, r)] Q_{abs}(a, \lambda) a^2 n(a) \, da$$

relative number of grains in the size intervall a and a + da

Warm grains: for small grains the efficiency factors at IR wavelengths are smaller than unity and:

$$B[\lambda, T(a, r)] Q_{abs}(a, \lambda) \ll B[\lambda, T(a, r)]$$

The measured IR color temperature is very often higher than the black body temperature at the corresponding heliocentric distance → indication for small grains

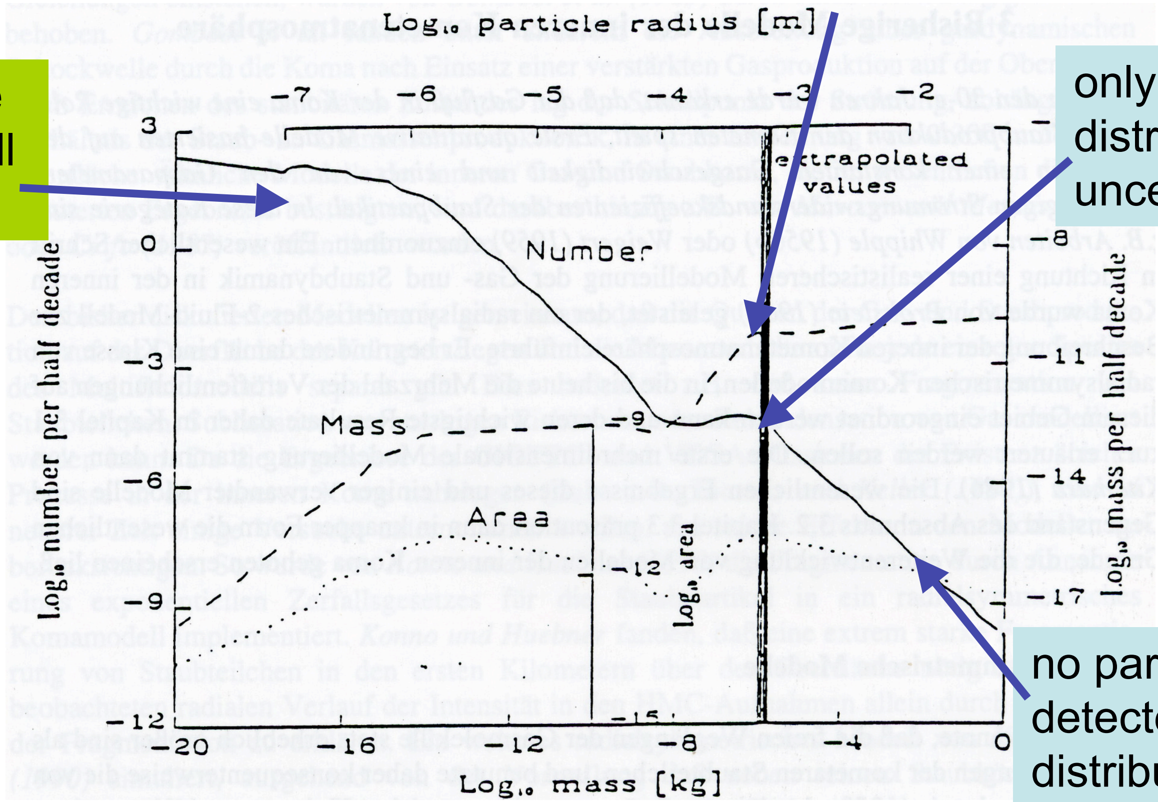
The dust grain size distribution

The dust size distribution has been measured insitu for comet P/Halley and 81P/Wild 2.

The dust mass is concentrated in few large particles!

most particles are measured at small radii.

only few particles, distribution uncertain



no particles detected $>10^{-3}$ m, distribution extrapolated

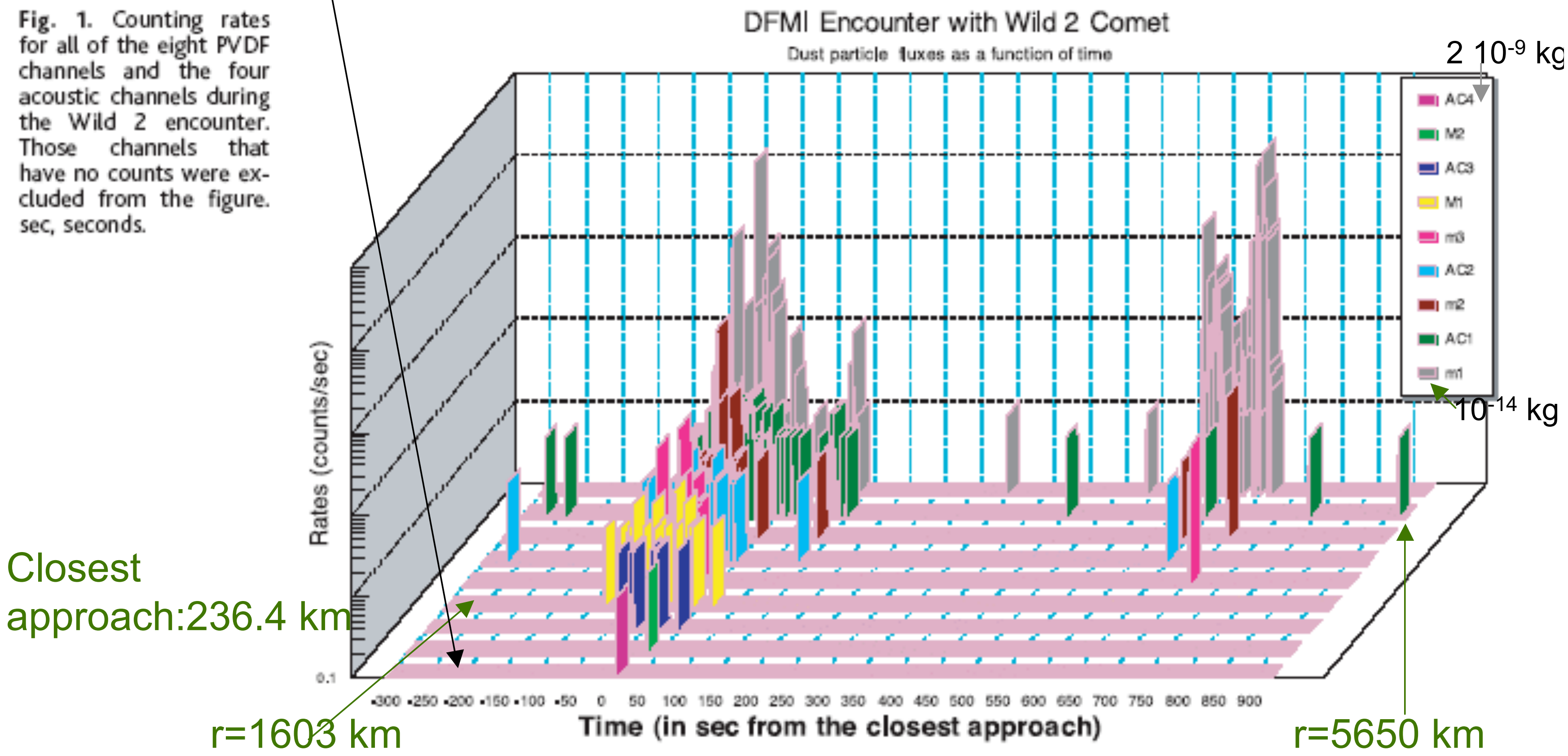
The mass is dominated by few large particles!

H. Rauer Saas Fee 06; McDonnell et al. 1989

assumed density: 1 g cm^{-1}

Clusters of particles seen during STARDUST fly-by Comet 81P/Wild 2 - maybe detecting a truncated size distribution?

Fig. 1. Counting rates for all of the eight PVDF channels and the four acoustic channels during the Wild 2 encounter. Those channels that have no counts were excluded from the figure. sec, seconds.

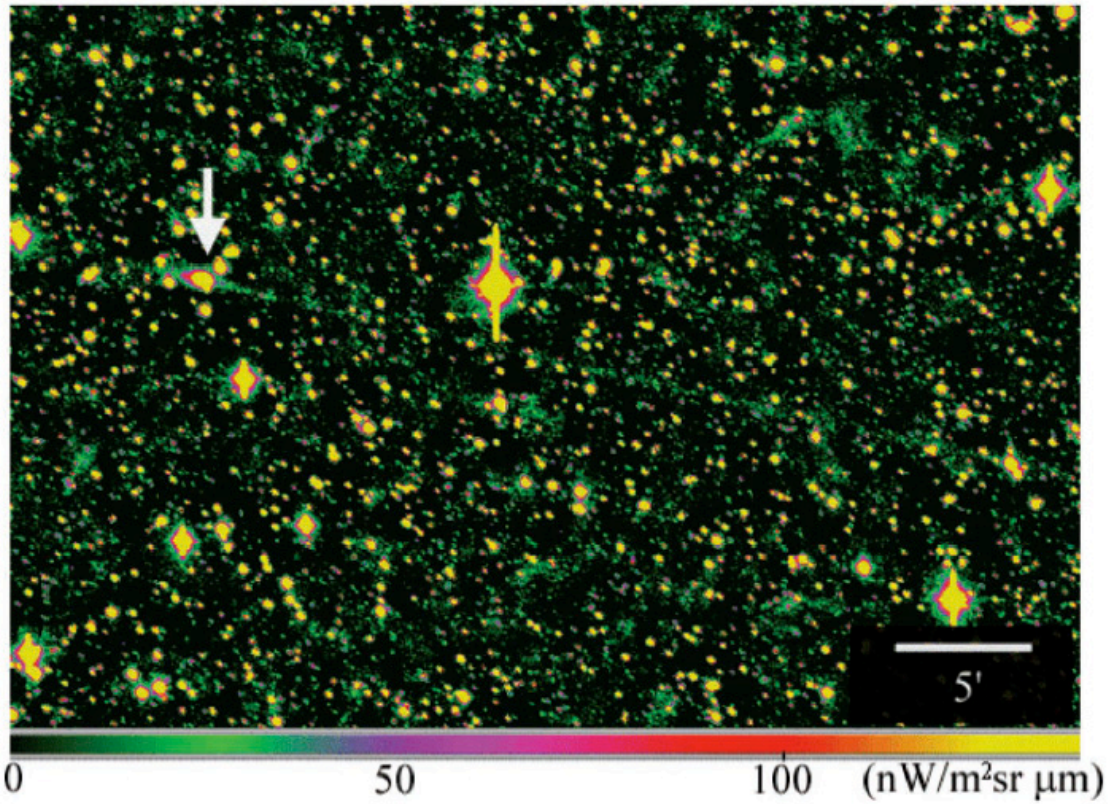


- Countings were not unitform throughout the coma: two high activity periods
- during second period almost no particles in accoustic sensor

H. Rauer Saas Fee 06; Tuzzolino et al. 2004, Science 304, 1776

Comet Dust trails show mm-size grain are released

- Large dust particles have small β
- Therefore, they remain on similar orbits than the parent comet
- They form dust trails along the orbit of the comet
- They are observed mainly in the IR (large particles)



Ishiguro et al. 2003, ApJ 589, L101

FIG. 2.—Dust trail image of the comet 81P/Wild 2 observed 2003 February 3. The coma is located at the position indicated by the arrow. The classical dust tail composed of small grains spreads toward the upper left, and the dust trail extends toward the lower right.

Spitzer MIPS views comet trails: 24 μm images show that a considerable mass of rocky materials are released.
mm-size grains are released and are seen many months later along the comet‘s orbit.

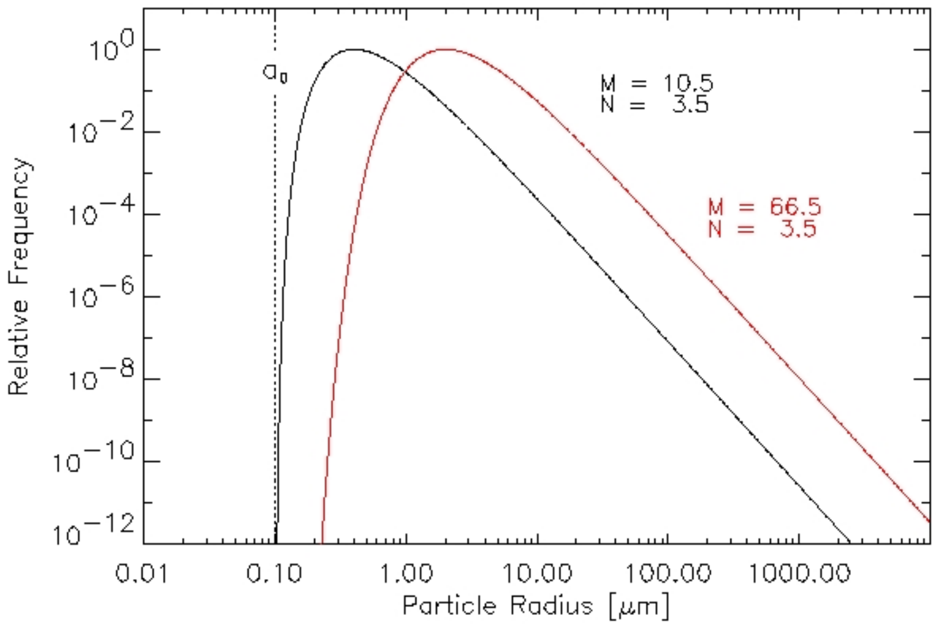
Grain Size Distribution

Typically used size distribution function:

$$f(a) = \overline{N} \cdot \left(1 - \frac{a_0}{a}\right)^M \left(\frac{a_0}{a}\right)^N$$

(Hanner 1982, in *Cometary Exploration II*)

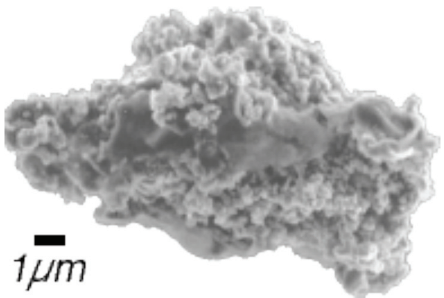
$\overline{N}$: scaling factor, a: particle radius



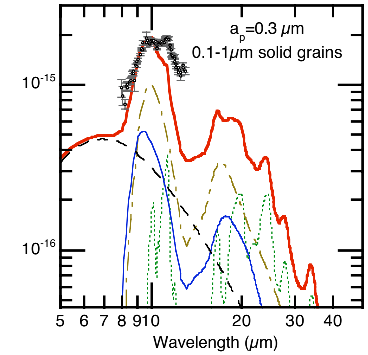
H. Rauer Saas Fee 06

a_0: lower size limit

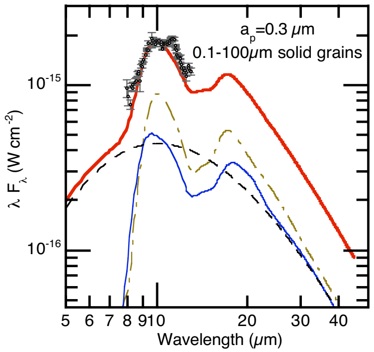
(smallest building blocks of fluffy aggregates? Typical size of IDP subgrains is 0.1μm.)



Mineralogy from Thermal Emission Modeling of IR Spectral Energy Distributions

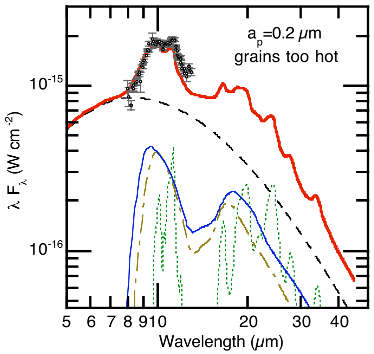


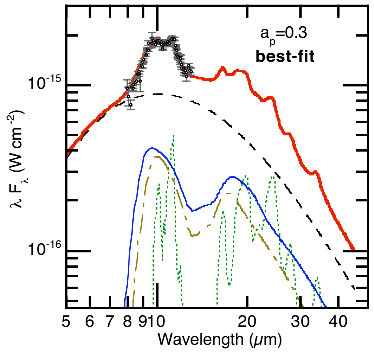
Submicron Mg-rich crystals are cooler than submicron Mg-Fe amorphous silicates, so the 11.2μm feature is difficult to detect if crystals are 1/4 of total mass (i.e., equal masses of Amorphous carbon, amorphous olivine & pyroxene, crystalline olivine)

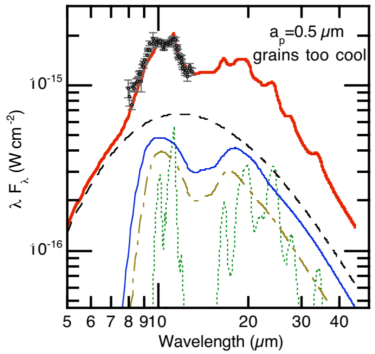


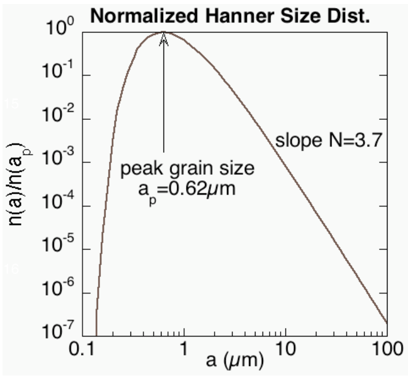
Grain size distribution extending from submicron to 100μm needed to longer wavelength (cooler emission) in SED

Grain size at which size distribution peaks can be constrained:

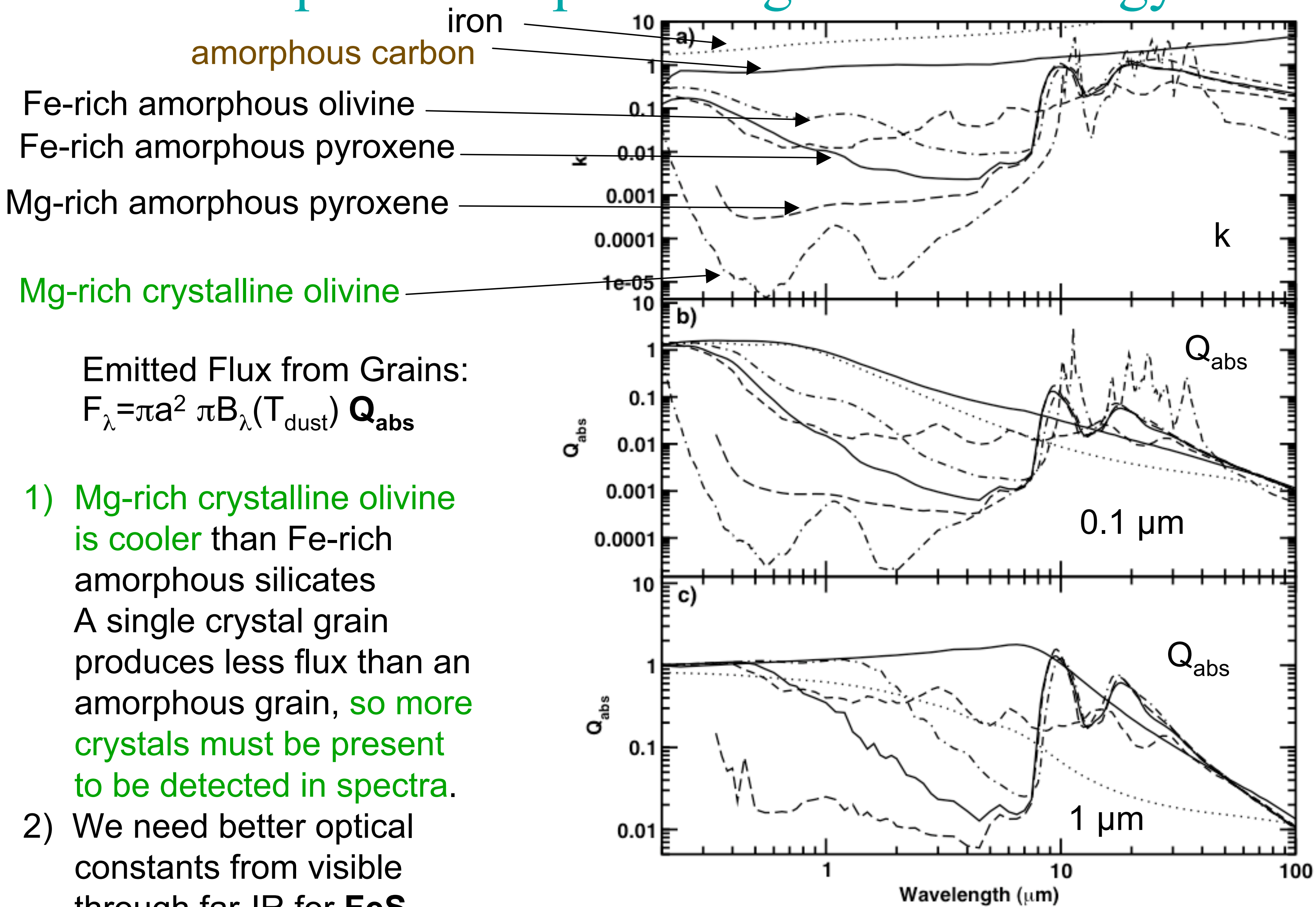








PPD Opacities depend on grain mineralogy

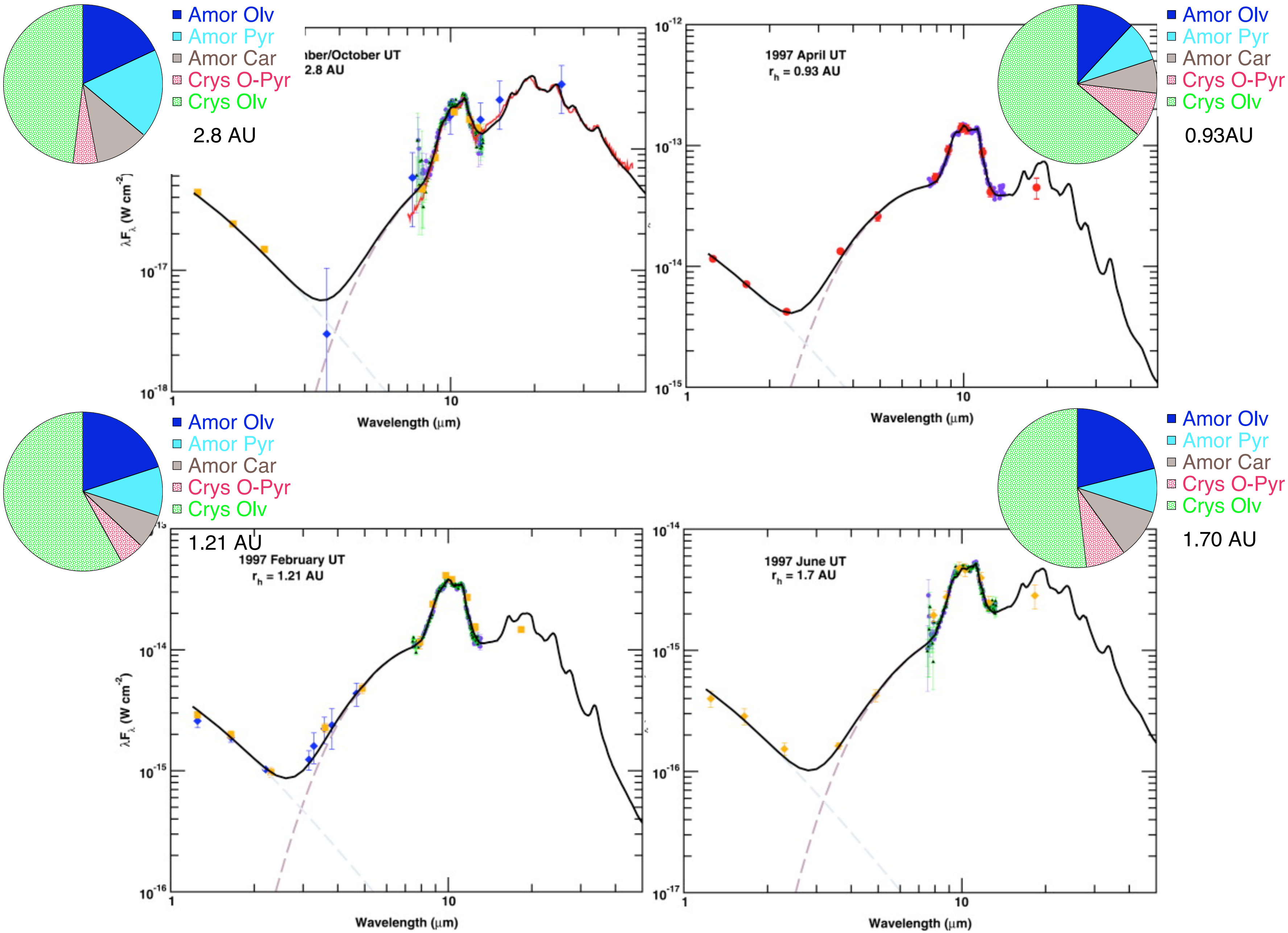


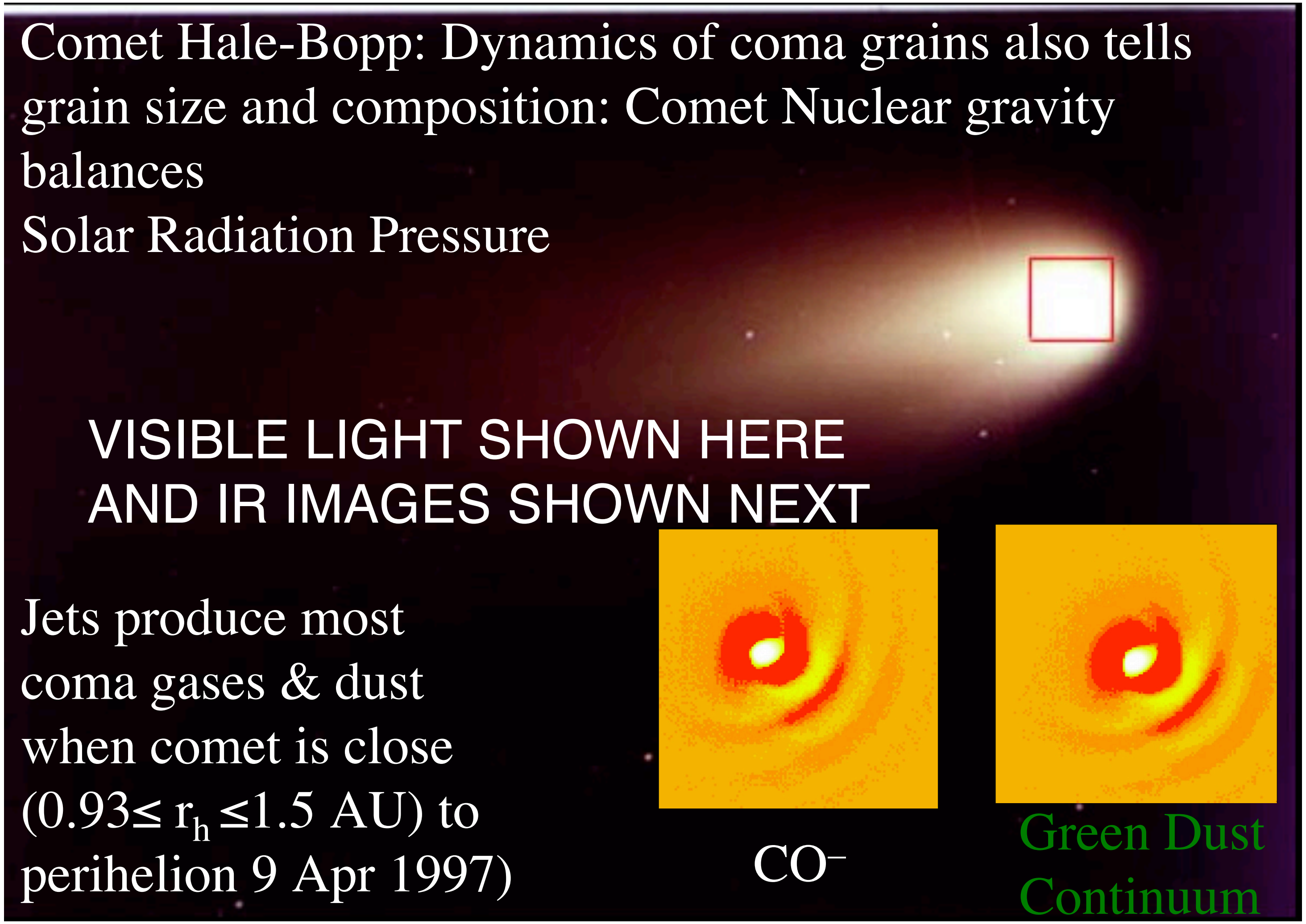
Emitted Flux from Grains:

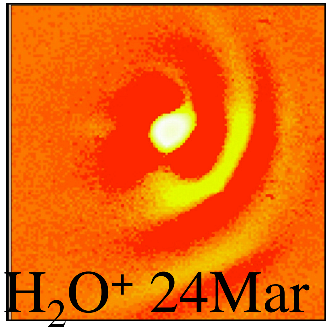
$F_\lambda = \pi a^2 \, \pi B_\lambda(T_{dust}) \, \mathbf{Q_{abs}}$

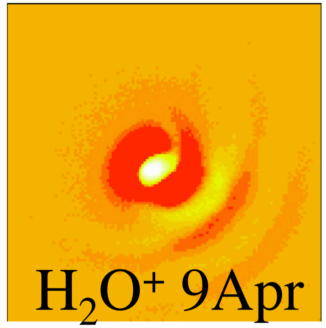
1) Mg-rich crystalline olivine is cooler than Fe-rich amorphous silicates
A single crystal grain produces less flux than an amorphous grain, so more crystals must be present to be detected in spectra.
2) We need better optical constants from visible through far-IR for **FeS.**

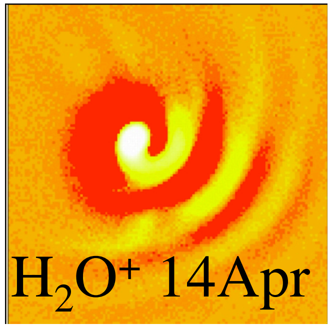
Evolution of Hale-Bopp's submicron mineralogy with heliocentric distance



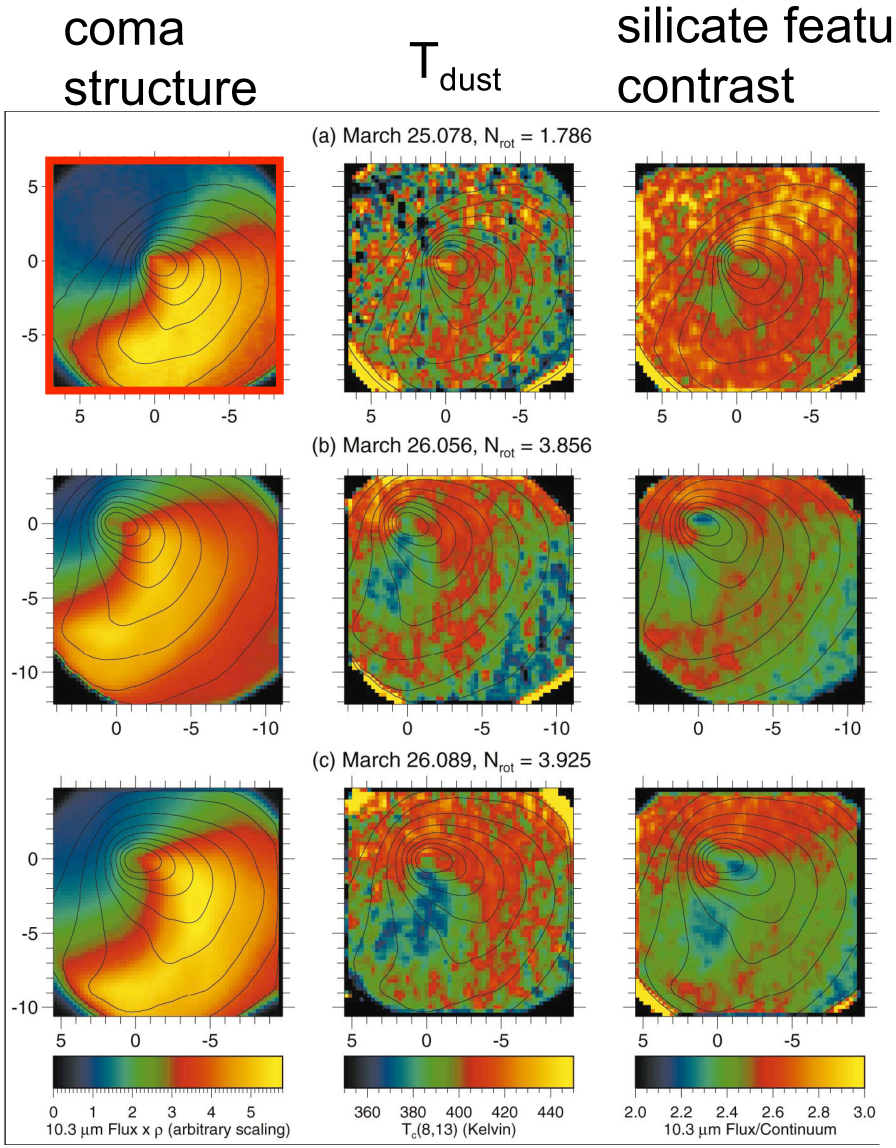

Comet Hale-Bopp: Dynamics of coma grains also tells grain size and composition: Comet Nuclear gravity balances
Solar Radiation Pressure
VISIBLE LIGHT SHOWN HERE
AND IR IMAGES SHOWN NEXT
Jets produce most coma gases & dust when comet is close ($0.93 \leq r_h \leq 1.5$ AU) to perihelion 9 Apr 1997)
CO^-
Green Dust Continuum

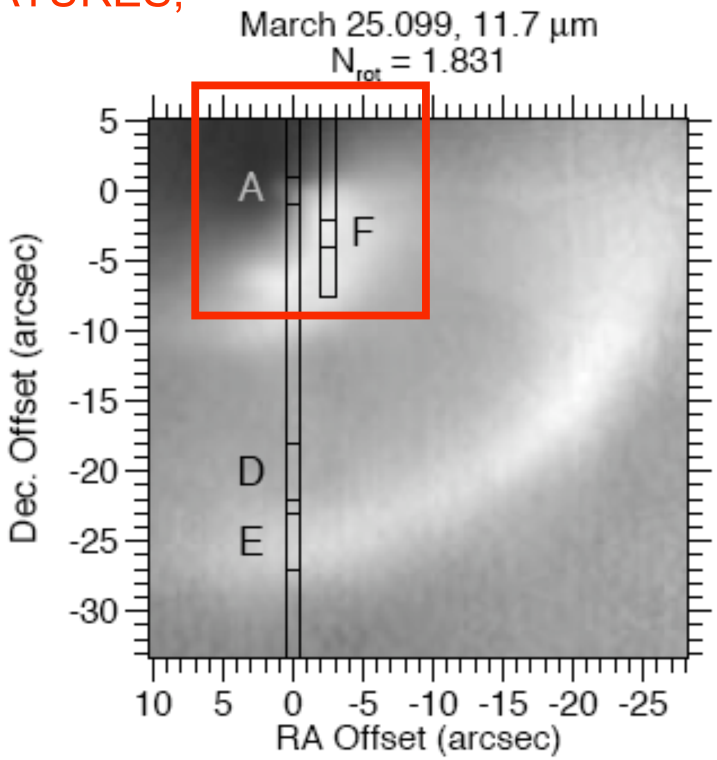

H_2O^+ 24Mar

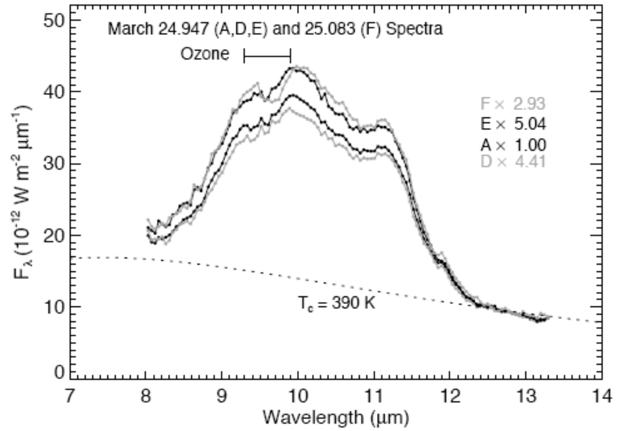

H_2O^+ 9Apr

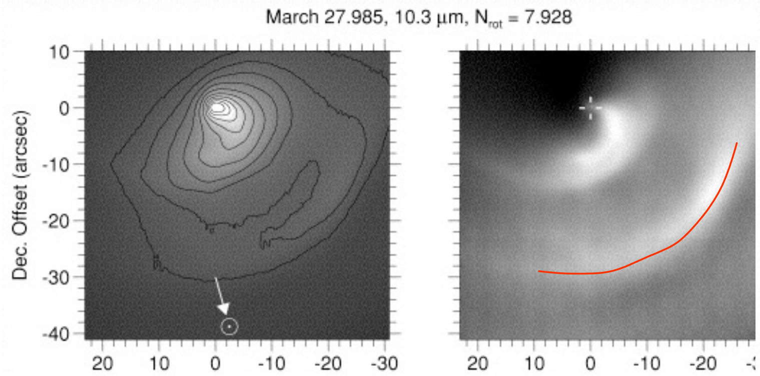

H_2O^+ 14Apr

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



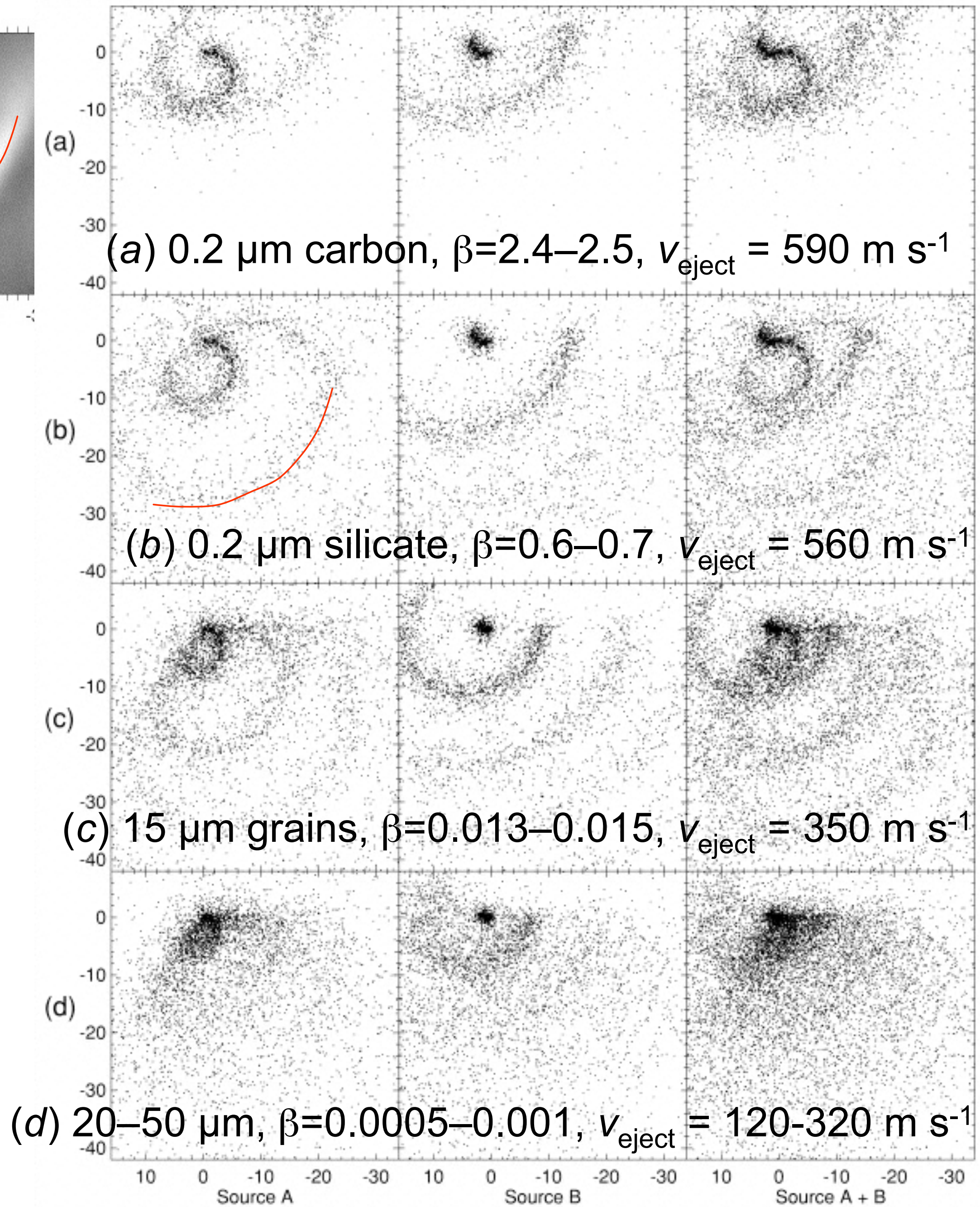




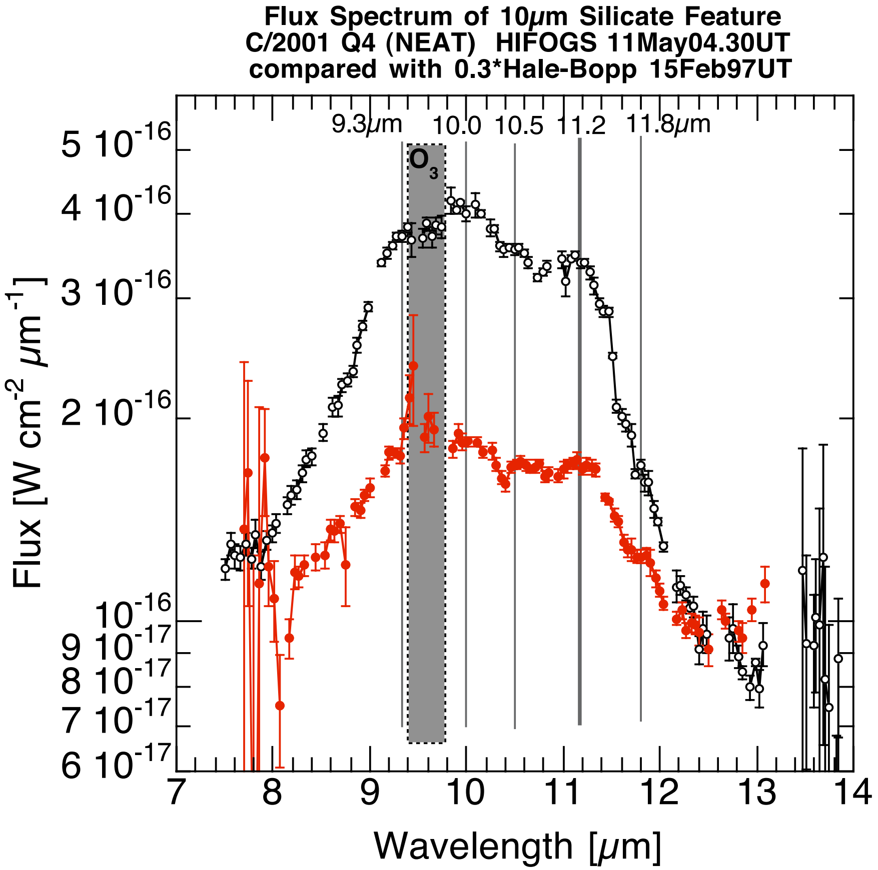


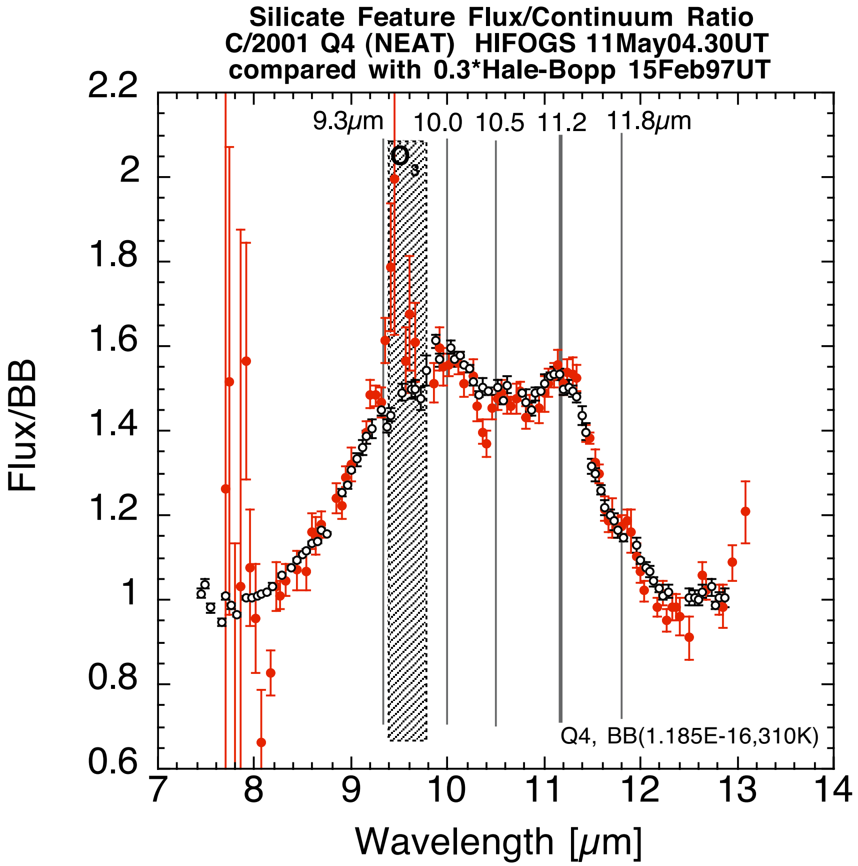
10µm INFRARED LIGHT

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: $\beta_{silicate} < \beta_{carbon}$



C/2001 Q4 (NEAT) & Hale-Bopp have similar silicate mineralogy,
both have strong jet activity & crystal/amorph.+cryst. ≈0.7
C/2001 Q4 has a smaller & variable silicate-to-amorphous carbon ratio,
which lowers the contrast (or ‘strength’) of the silicate feature.

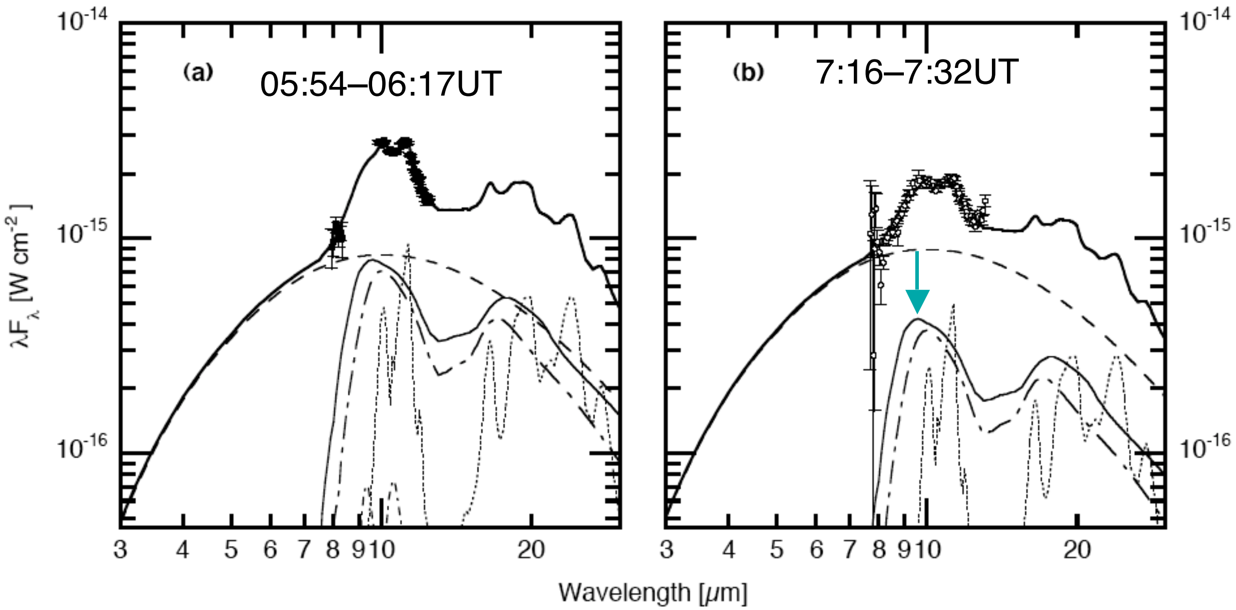




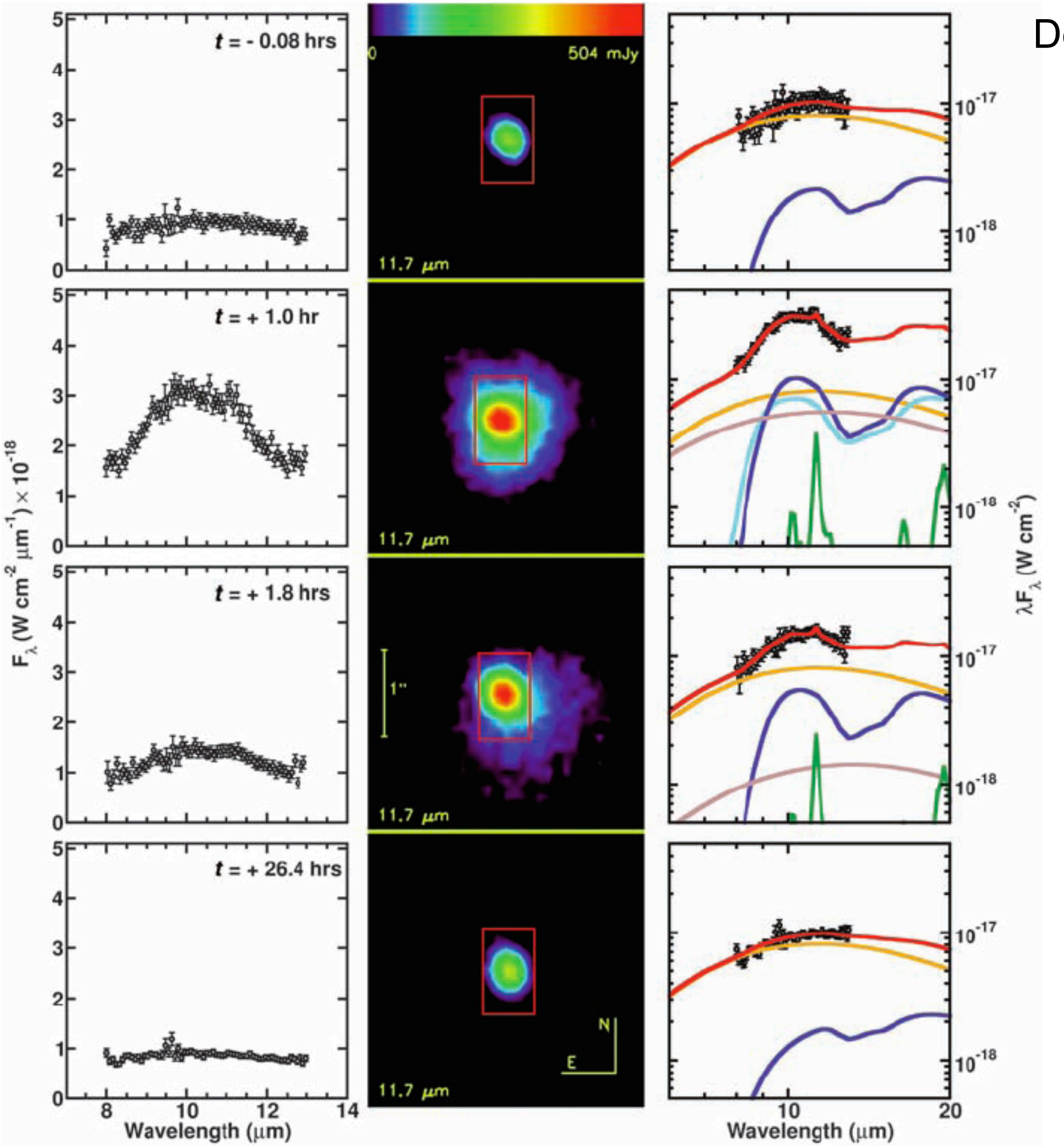
Mineralogy is inhomogeneous: the relative abundances of Amorphous Carbon and Silicates vary in coma, assoc. with 'jets'.

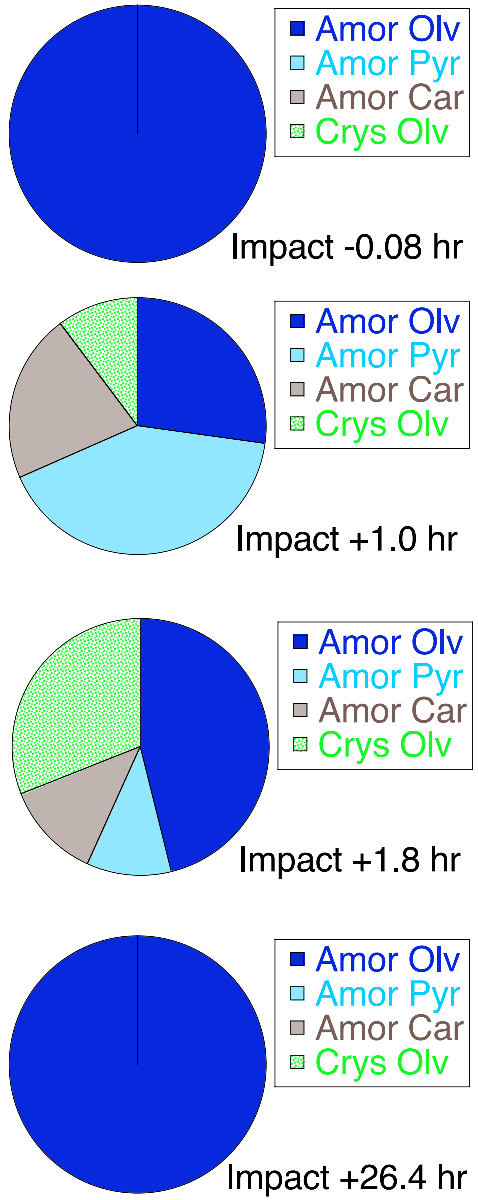
C/2001 Q4's silicate **feature drops in contrast** (height) over 1.5 hours, as jets move grains through beam and dust composition changes: there are **fewer silicate grains relative to amorphous C grains**.

C/2001 Q4 (NEAT) on 2004 May 11



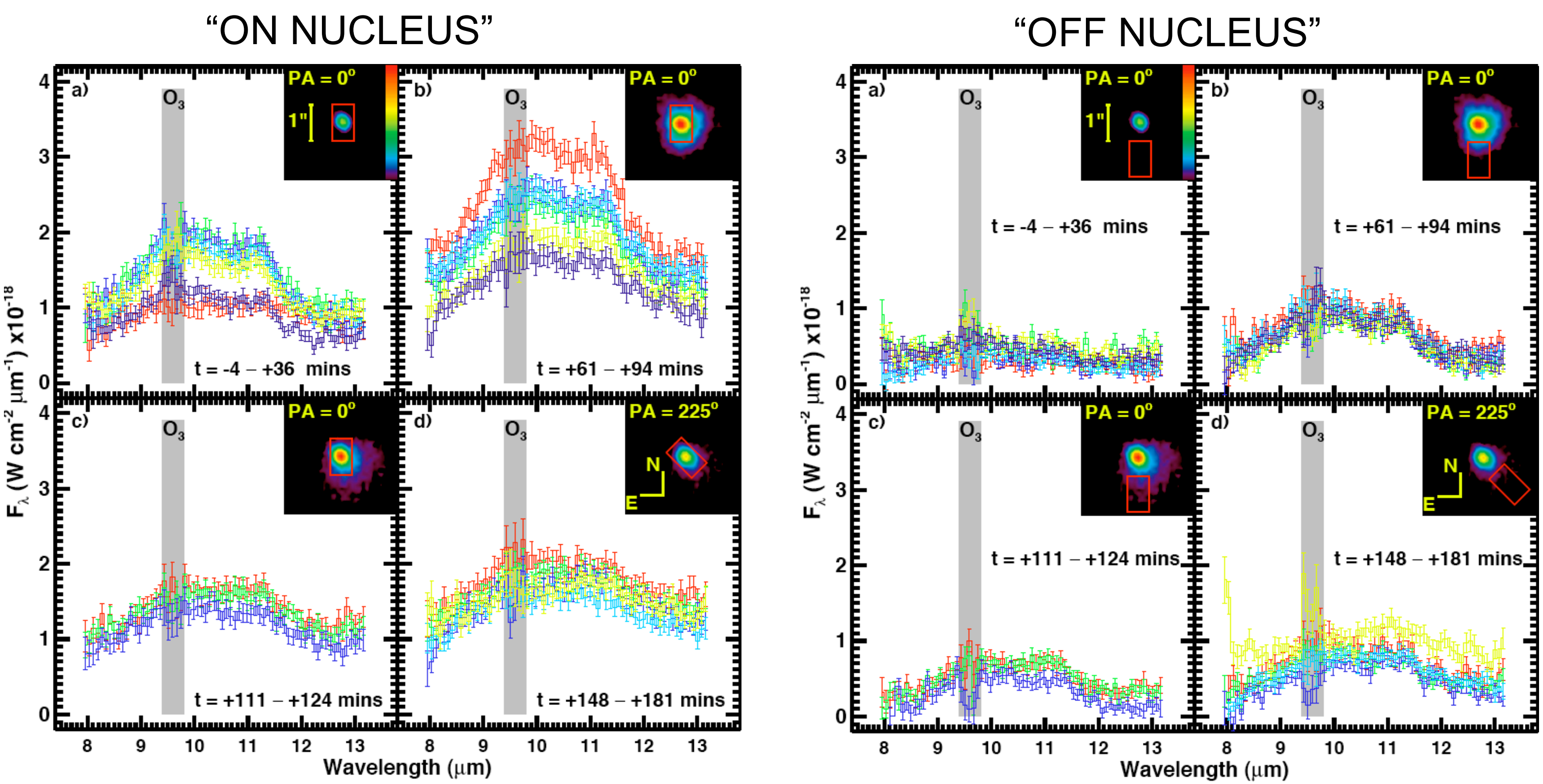
Deep Impact released Crystals





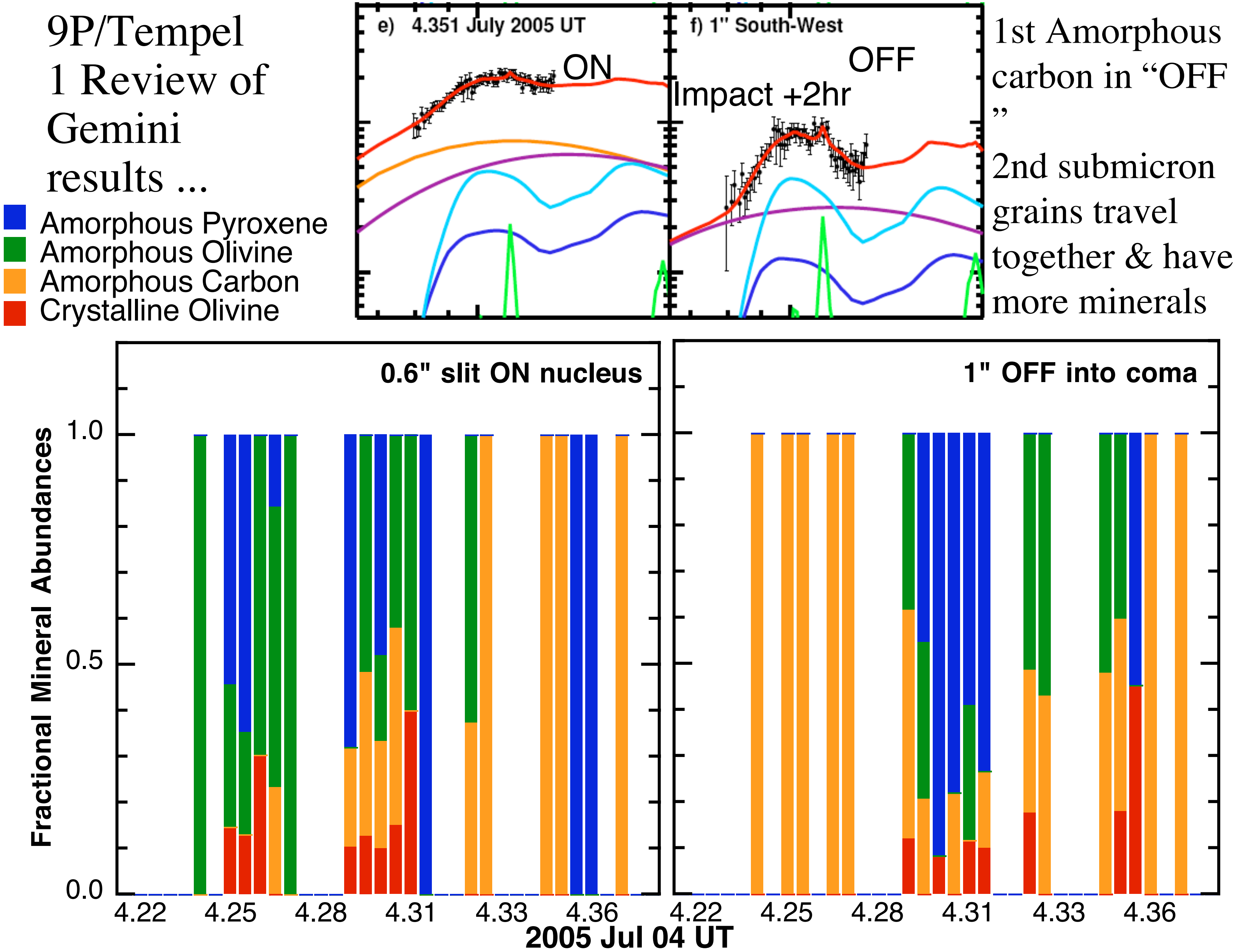
Harker etal2005, etal 2006

GEMINI+Michelle Full Data Set (every 7min)



Harker, Woodward, Wooden (2006) Icarus, accepted.

9P/Tempel 1 Review of Gemini results ...

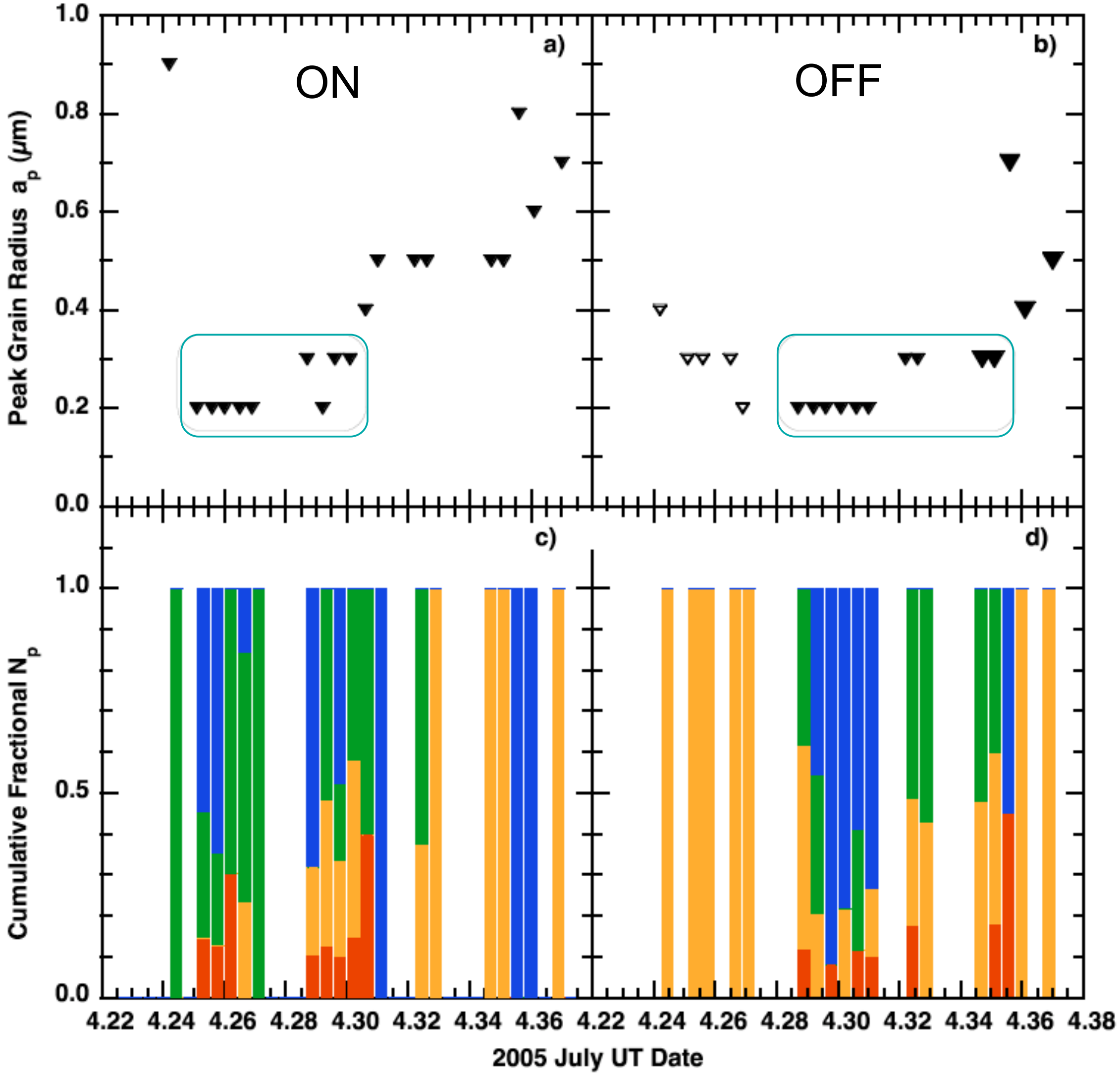


1st Amorphous carbon in "OFF"

2nd submicron grains travel together & have more minerals

adapted from Harker, Woodward, Wooden (2006) Icarus, accepted.

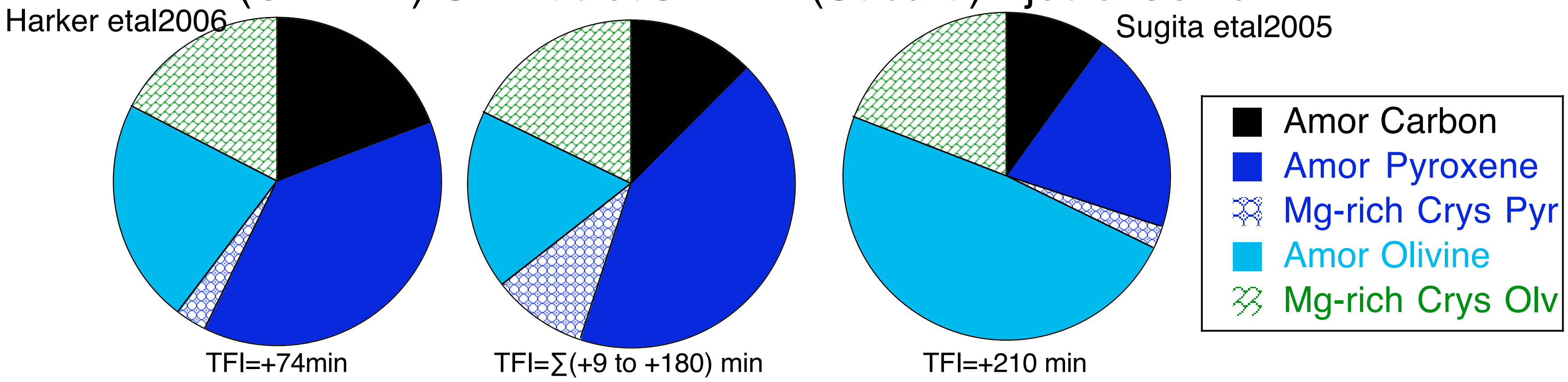
Smallest grains are ON nucleus and sustained for 30 min, but takes time (>30 min) for these smallest grains to reach maximum 1” OFF into coma
Grain size dist with smallest grains have 4 minerals or are ensembles of 4 minerals.
Larger grains persist longer ON and OFF (move slower), and have 1 or 2 minerals.



Deep Impact Ejecta-Coma: Comparison of Observation-Modeling Results

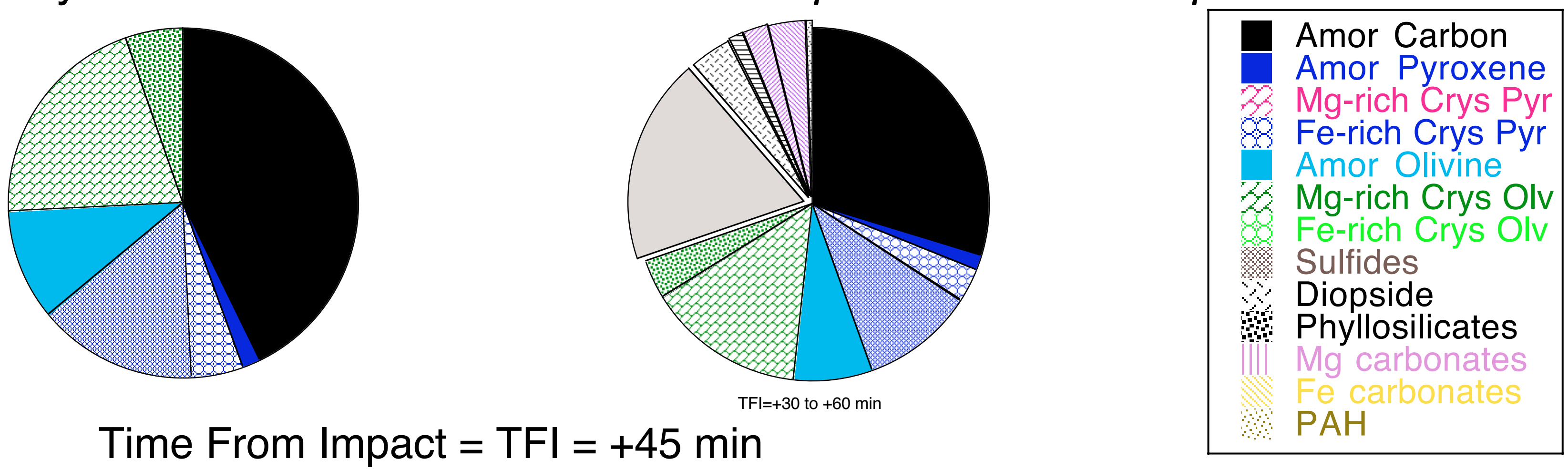
0.1–1 μm Portion of Grain Size Distribution Relative Mass Fraction

(GEMINI) On-Nucleus (Subaru) Ejecta-Coma



Grain Surface-Area Weighted Mass Fraction (Spitzer)
Only for Minerals Constrainable with 10μm and with 5–37μm

Lisse etal2006



Time From Impact = TFI = +45 min

pie charts from Wooden, Woodward, Harker 2007 (DI as a world observatory event proceedings)

Where Deep Impact hit comet 9P/Tempel 1 the dominant mineral on the surface is Amorphous Carbon.

This result is not unexpected: Amorphous Carbon is present on the surfaces of outer icy bodies in significant quantities (~10–80%) see summary Table of near-IR reflectance spectra model fits.

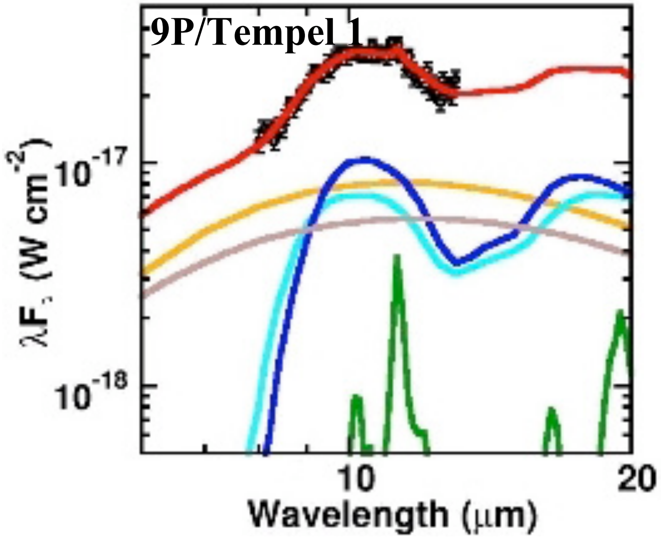
Object Class	Object Name	Amorphous Carbon	Titan Tholin [a]	Tritan Tholin [b]	Ice Tholin [c]	Kerogen Type II [d]	Water Ice	Olivine	A [e]	Refs
Centaur	2001 PT_{13}	0.7 10 μm	0.15 7 μm		0.12 10μm			0.03	0.09	**4**
Centaur Epoch1,2	2001 PT_{13}	0.7, 0.9	0.15, 0.05		0.12, 0		0, 0.05	0.03, 0	0.09 0.06	**4**, **13**, 2
Centaur	1998 SG_{35}					0.97	0.02	0.01		**4**, **13**, 10
Centaur	2000 QC_{243}					0.96	0.03	0.01	0.04	**13**, 11
Centaur	2001 BL_{41}	0.73		0.17	0.10				0.08	**4**, **13**, 14
Centaur Epoch1,2	1999 UG_5	0.66, 0.41	0.14, 0	0, 0.42		CH_3OH ice 0.03, 0	0.13, 0.17	0.04, 0	0.05	**13**, 1
Centaur	Pholus	carbon black	YES				YES $+CH_4$ ice		0.06	**13**, 6
Centaur	Chariklo	YES	YES	YES			~0.02			**13**, 12
Centaur	Asbolus	0.73		0.17	0.10				0.08	**13**, 19
Centaur	Chiron						YES when inactive 1996-2001			**13**, 16
TNO	2000 EB_{173}	YES	YES					Jarosite? [f]		**4**, 9
TNO	1999 TC_{36}	0.10	0.67		0.25		0.08			**4**, 11
TNO	1996 GQ_{21}	0.50	0.15		0.35					**4**, 11
KBO *Active*	1996 TO_{66}						YES strong			**18**
KBO	1999 DE_9	yes	organics yes				yes			**18**, 3, 14
KBO	2001 BL_{41}	yes	yes				yes			**18**
Trojan Asteroid Model1 Model2 Model3	Hektor	YES; G=graphite 0.2 0.01 0.4+0.15G						pyroxene, serpentine 0.4, 0.4 0.29, 0.7 0.45, 0		**8**, 7

Notes: [a] Titan Tholin $N_2:CH_4$=0.9:0.1 [15]; [b] Tritan Tholan: $N_2:CH_4$=0.999:0.001 [17]; [c] Ice Tholin $H_2O:C_2H_6$ [15]; [d] Kerogen Type II [ ]; [e] A means Albedo at 0.55μm; [f] Jarosite $KFe_3(SO_4)_2(OH)_6$

Refs: 1: Bauer et al. 2002; 2: Barucci et al. 2002; 3 Boehnhardt et al. 2002; **4**: Boehnhardt et al. 2004: 5: Brown et al. 1997; 6: Cruikshank et al. 1998; 7: Cruikshank et al. 2001; **8**: Cruikshank & Dalle Ore 2004; 9: de Bergh et al. 2003; 10: Dotto et al. 2002; 11: Dotto et al. 2003a; 12: Dotto et al 2003b; **13**: Dotto et al. 2004; 14: Doressoundiram et al. 2003; 15: Khare et al. 1984; 16: Luu et al. 2000; 17: McDonald et al. 1994; **18**: Meech et al. 2004; 19: Romon-Martin et al. 2002; 20: Sagan & Khare 1979.

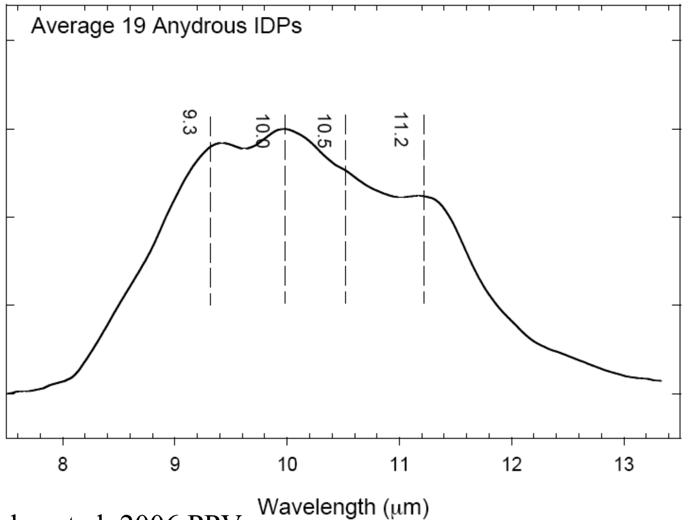
Summary of Comet Grains: Mineralogy & Structure from IR Spectral Energy Distributions and Anhydrous CP IDPs

Harker, Woodward, Wooden 2005, Science, 310, 278



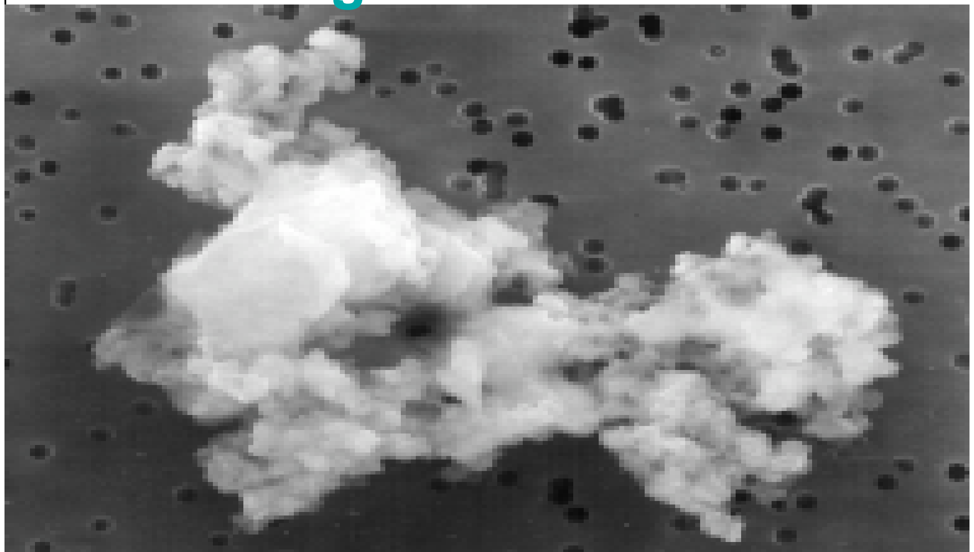
What is comet dust made of?

- **Amorphous Fe-bearing silicates: olivine $(Mg,Fe)_2SiO_4$, pyroxene $(Mg,Fe)SiO_3$**; porous, aggregate
- **Abundant amorphous carbon, or highly disordered, dehydrogenated**
- **Crystalline silicates** (when detected)
  - submicron in size, not porous
  - **Mg-rich [Mg/(Mg+Fe)>0.9]**
  - comparatively cooler than the amorphous silicates
  - comparatively abundant



Keller & Flynn 2000; Wooden et al. 2006 PPV

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

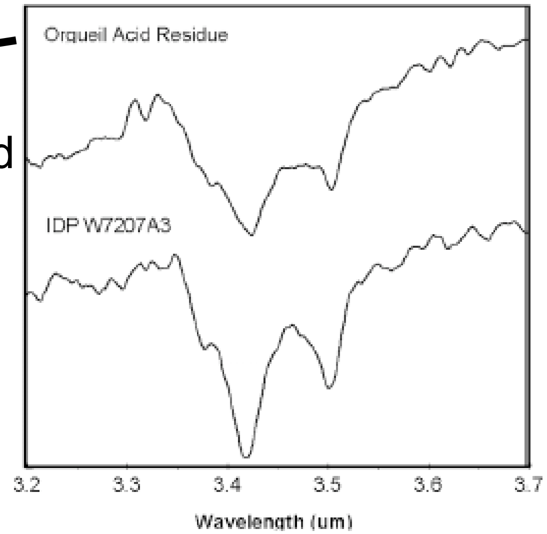


Anhydrous **C**hondritic **P**orous **I**nterplanetary **D**ust **P**articles are highly porous **aggregates of disequilbrated minerals**: amorphous silicate spherules (GEMS), silicate crystals, FeS crystals, “glued” together with Carbon.

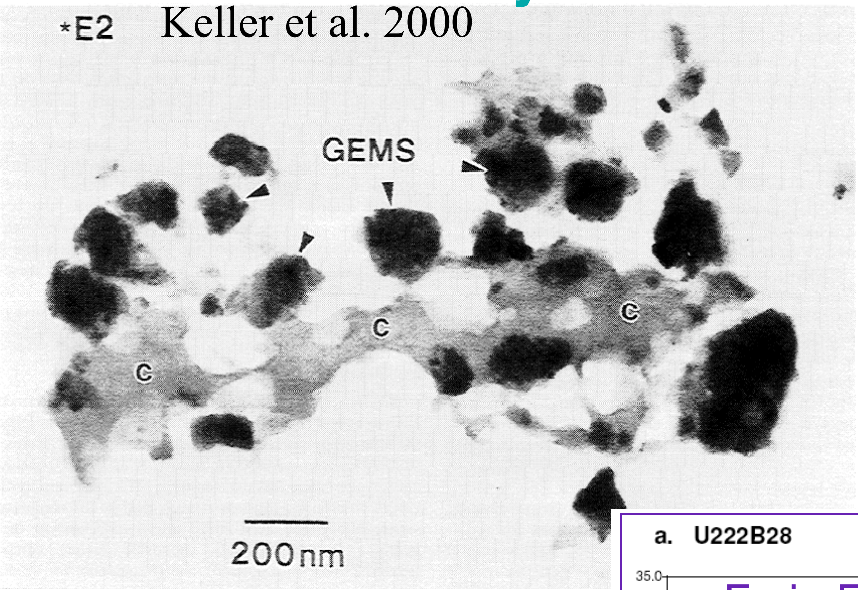
⇨ **GRAINS AGGREGATED AFTER CRYSTALS FORMED**

Aggregate Matrix is Carbon: amorphous, aliphatic, little aromatic

Spectra of acid-etched IDP thin section shows aliphatic bonds

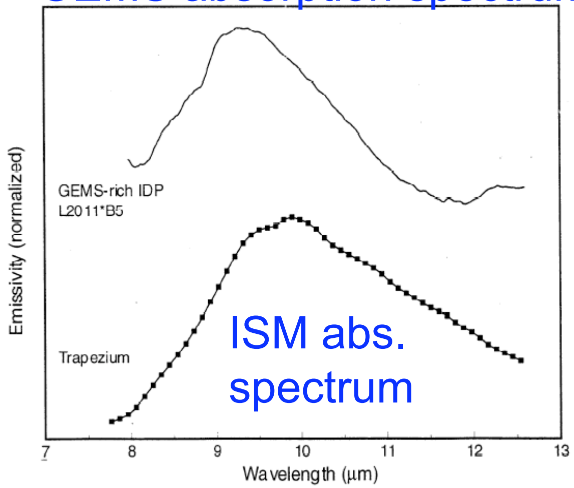


Comet Dust Mineralogy & Structure from Anhydrous Chondritic Porous IDPs

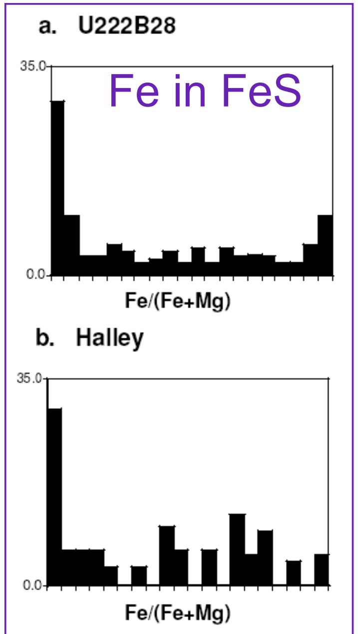


Keller et al. 2000

GEMS absorption spectrum



Keller etal 2003 JGR



Bradley etal 1999

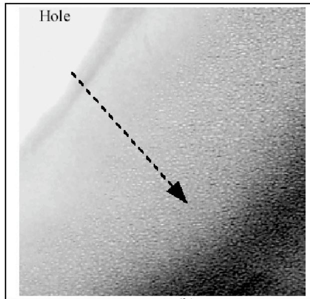
- average of IDPs have 12% C; individual IDPs 5-90% C
- CP IDPs are abundant in Fe-rich Amorphous Silicates: Amorphous Olivine and Pyroxene (GEMS-like grains)
- CP IDPs contain Mg-rich crystals (Fe/Fe+Mg<0.05), often >20% by mass
- Most of Fe is in FeS

Note: Min et al. (2005) deduce FeS content in Hale-Bopp

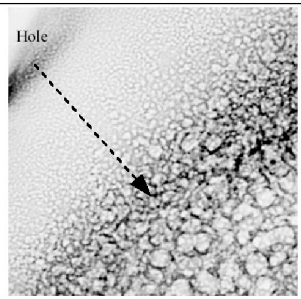
Low energy cosmic rays (e.g., 4-50 keV He^+) amorphize and reduce Fe: GEMS and Mg-Fe amorphous silicates have smooth IR spectral resonant shapes, but there are differences.
Laboratory amorphous silicates or an ensemble of GEMS better match comet spectra.

He^+ Ion Bombardment in ISM of Mg-rich crystalline silicates forms porous amorphous silicates and nanophase Fe

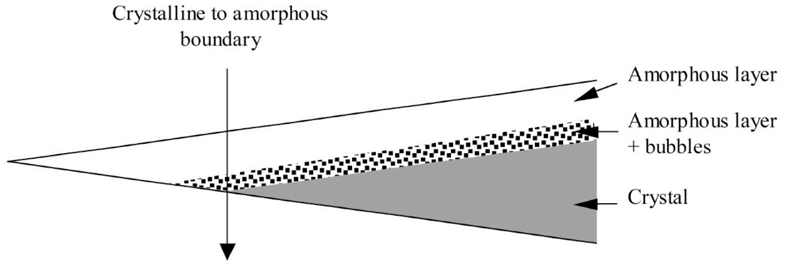
Carrez etal 2002



Irradiation influence at 4KeV of 10^{17} He^+/cm^2

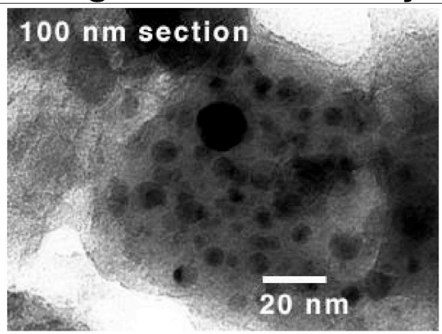


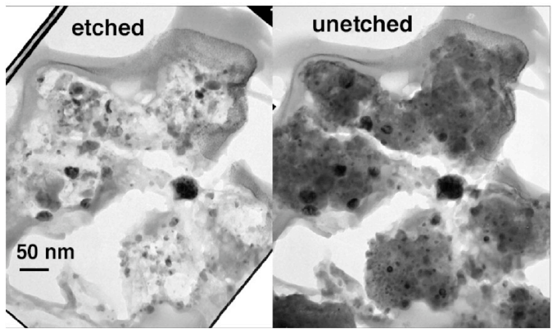
Irradiation influence at 4KeV of 5×10^{17} He^+/cm^2



Stardust Crystals Amorphized by Ion Bombardment in ISM

Mg-rich Stardust Crystals Annealed by Ion Bombardment in ISM

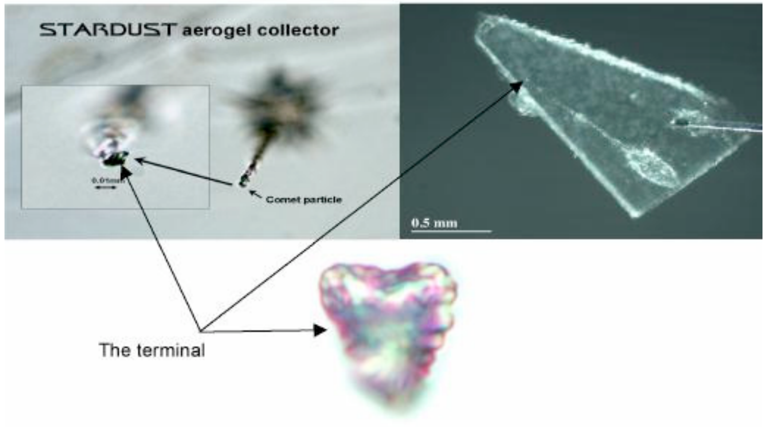




nano-phase Fe & FeS make grains absorbing

Brownlee etal 2000 LPS

Mineralogy and Structure from STARDUST MISSION Samples

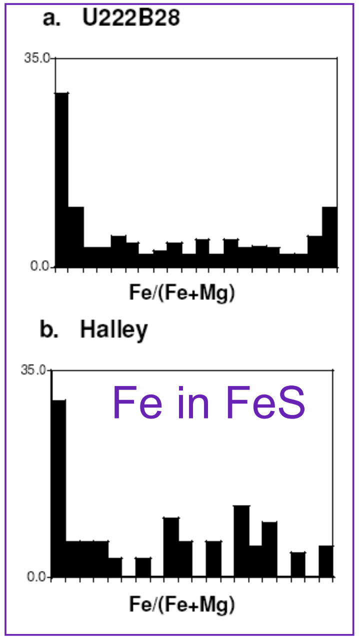


- CAI-type minerals (highest temp solar nebula condensates)
- Mg-rich silicate crystals
- more minerals to be reported...?
- difficult due to aerogel capture:
  Fe-Mg amorphous silicates
  carbonaceous/organic

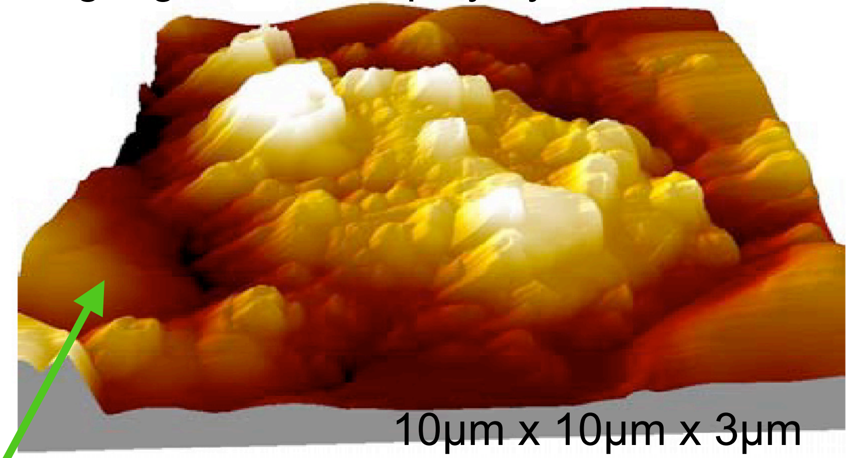
Mineralogy and Structure from Comet Halley Time-Of-Flight Mass Spectrometer Measurements

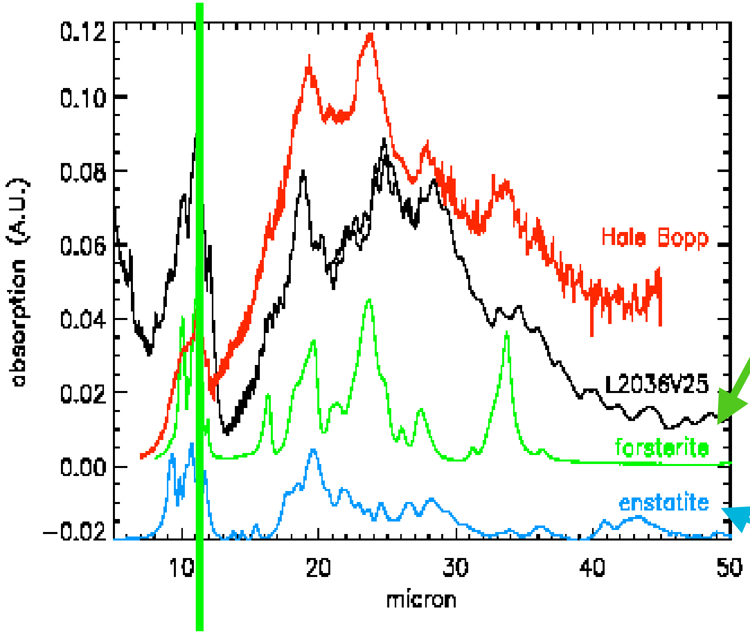
- 50% are siliceous+CHON
- 25% are CHON: 8% of grains are C (amorphous?)
- 25% are siliceous: mostly Mg-rich pyroxene, lesser Mg-Fe olivine, silicates containing Sulphur, FeS
- 70% of Fe is in **FeS** grains, 30% in silicates

Schulze, Kissel, Jessberger 1997 in From Stardust to Planetesimals

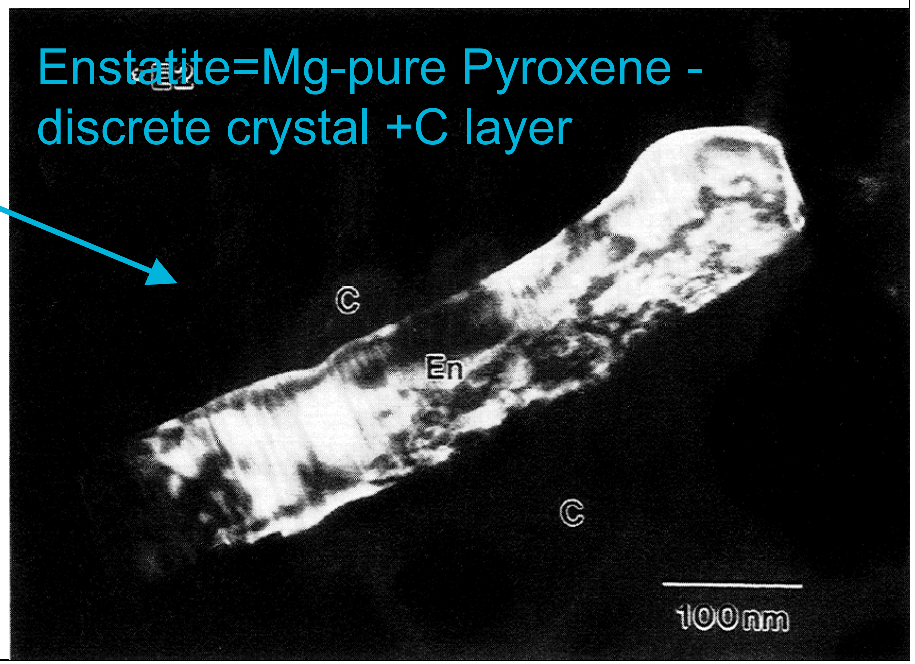


Mg/Mg+Fe≈0.75 polycrystalline Olivine



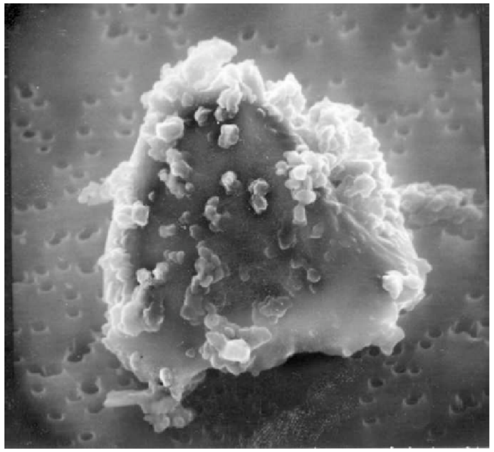


Molster etal 2003 LPS

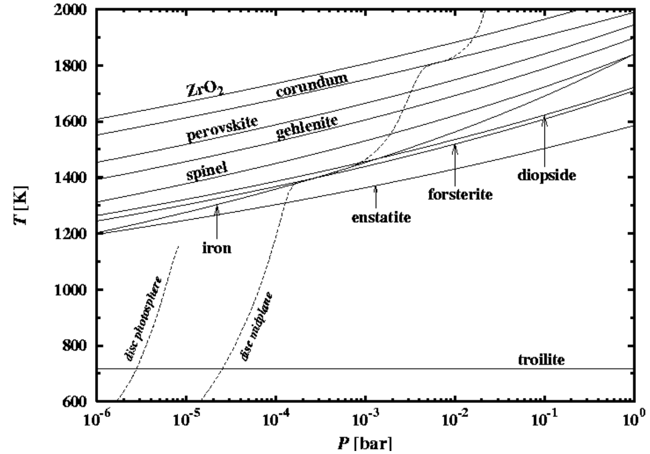


Formation Mechanisms for Crystalline Silicates are Gas-Phase Condensation and Annealing (Devitrification)

Mg-rich Crystals may Condense from Nebular Gases at ~1400 K

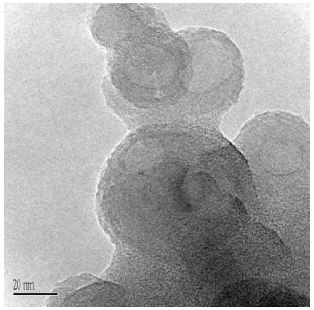


Bradley et al. 1999;

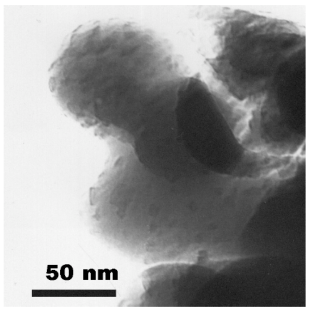


Wooden et al. 2006 PPV; Gail

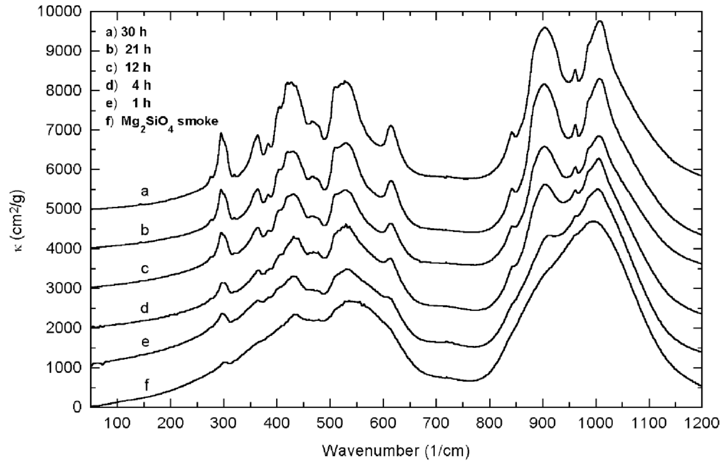
Mg-rich Crystals may be Annealed from Mg-rich Amorphous Silicates at 900K – 1200K



Mg-rich Amorphous Silicate Smoke, formed by laser ablation of melt



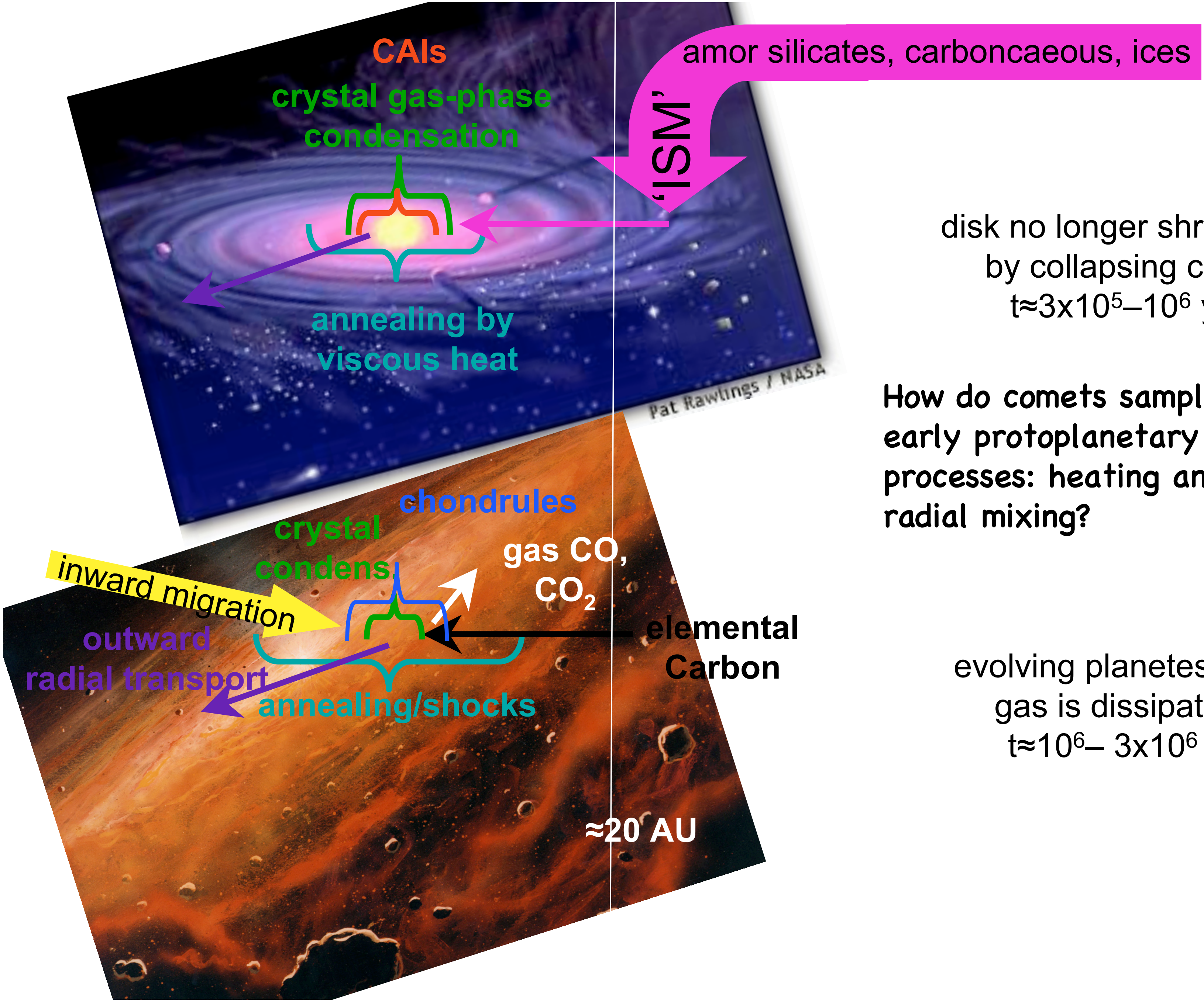
Annealed Mg-Olivine Smoke: crystals in amorphous and polycrystalline matrix



Fabian et al. 2000, A&A, 364, 282

Summary of Annealing Experiments (Wooden, Harker, Brearley in Chondrites and the PP Disk)

Process	Material *Method*[a]	Amorphous Properties[b]	T_c[K][c]	τ_c [hr] start	τ_c [hr] complete	E_a/k [K] start[d]	E_a/k [K] complete	IR crys. features[e]
Fabian et al. (2000)								
quenched melt[f]	$MgSiO_3$ *SEM*	ens sheet	1121	0.05	0.08	40200	40700	ens
quenched melt[f]	$MgSiO_3$ *SEM*	ens powder 2.5–5µm	1080	1	1.5	41900	42400	ens
			1060	2.5	3.17	42000	42400	
			1030	12	25	42500	43300	
			1000	>50	—		>42700	
laser ablation	$MgSiO_3$ *TEM*	for+silica smoke[g]	1000					for+SiO_2
laser ablation	Mg_2SiO_4 *TEM*	for smoke[g]	1206		1		46800	for+SiO_2+
			1000	1.33	12	39200	41300	MgO
laser ablation	SiO_2 *XRD*	silica smoke[g]	1220	4	5	49100	49300	SiO_2
Brucato et al. (2002)								
laser ablation	Mg_2SiO_4 *FESEM* *TEM*	for smoke[g]	1073		1		41700	for
			1023	4	>15	41100	>42500	
			973	72	>144	41900	>42600	
laser ablation	**$FeSiO_4$** *FESEM* *TEM*	fa smoke[g]	1273		1		49400	fa
			1073	1	315	41700	47800	fa+SiO_2
			873	2	216	34500	38600	fa, SiO_2?
			773	>288	—	>34400		fa
laser ablation	MgO-SiO_2	for smoke[g]	1273	1		45500		for
			1173	>1		>41700		
			1073					
laser ablation	MgO-SiO_2-Fe_2O_3	Fe-bearing ol smoke[g]	1273		1		49400	for
Brucato et al. (1999)								
laser ablation	$MgSiO_3$	ens smoke[g] .02–.04µm	1273		0.12		46700	ens
			1073	24	311	45100	47800	
Hallenbeck et al. (1998)								
vapor condensa-tion	SiH_4+Mg +H_2+O_2 *AEM*	MgSiO smoke[h]	1027	6	*stall*	41700		for+SiO_2
			1027	*50*	192	44300	45300	
Thompson et al. (2002)								
gel desiccation	$MgSiO_3$ *XRD*	for gelatinous precipitate	873	4		35100		for
			933		4		37500	for
			970	24		40700		for+ens
			1000		4		40200	for+ens

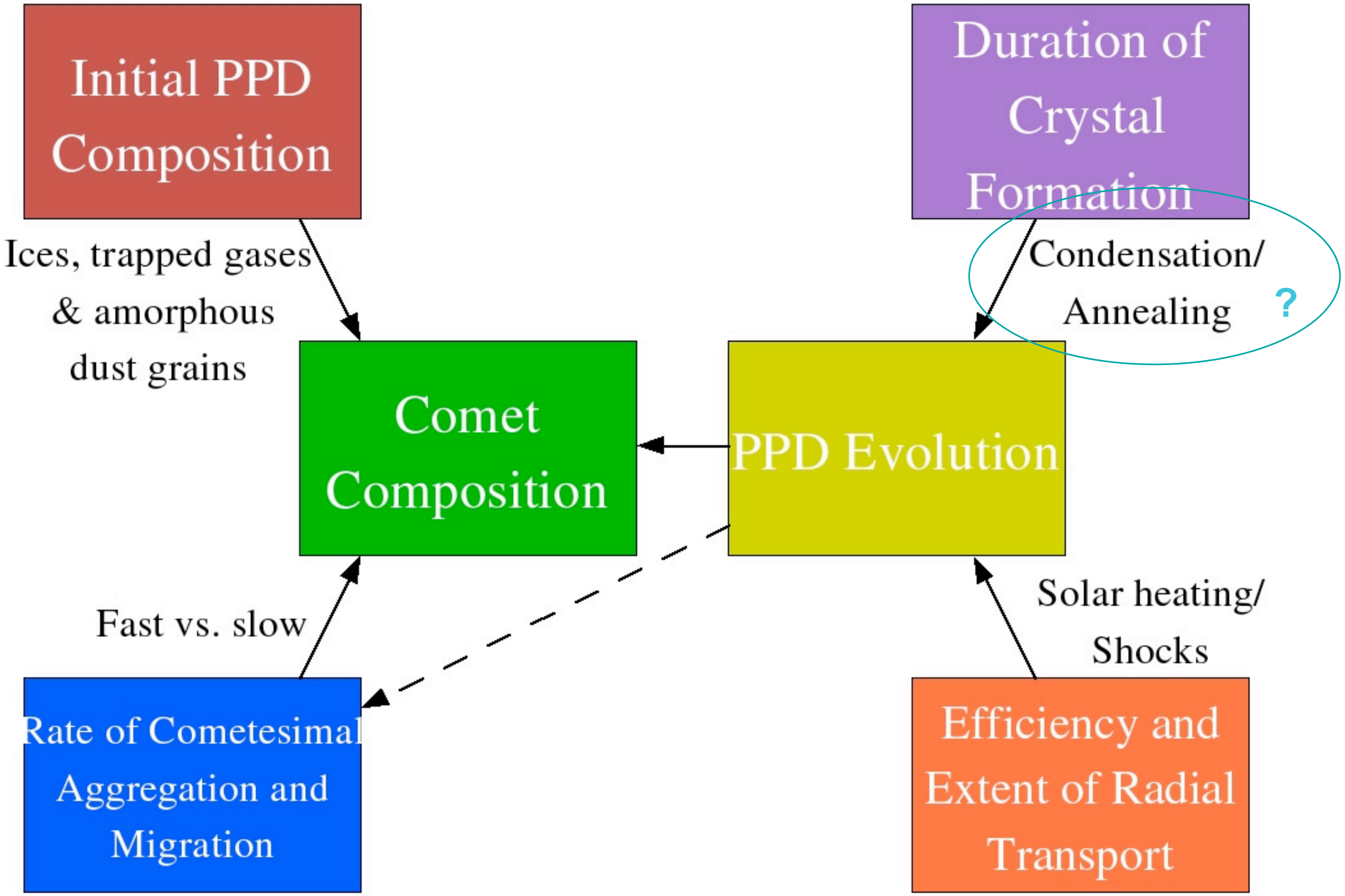


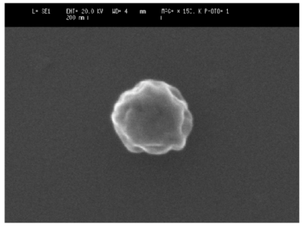
disk no longer shrouded
by collapsing core
t≈$3x10^5$–10^6 yr

How do comets sample early protoplanetary disk processes: heating and radial mixing?

evolving planetesimals
gas is dissipating
t≈10^6– $3x10^6$ yr

What Determines Comet Composition?



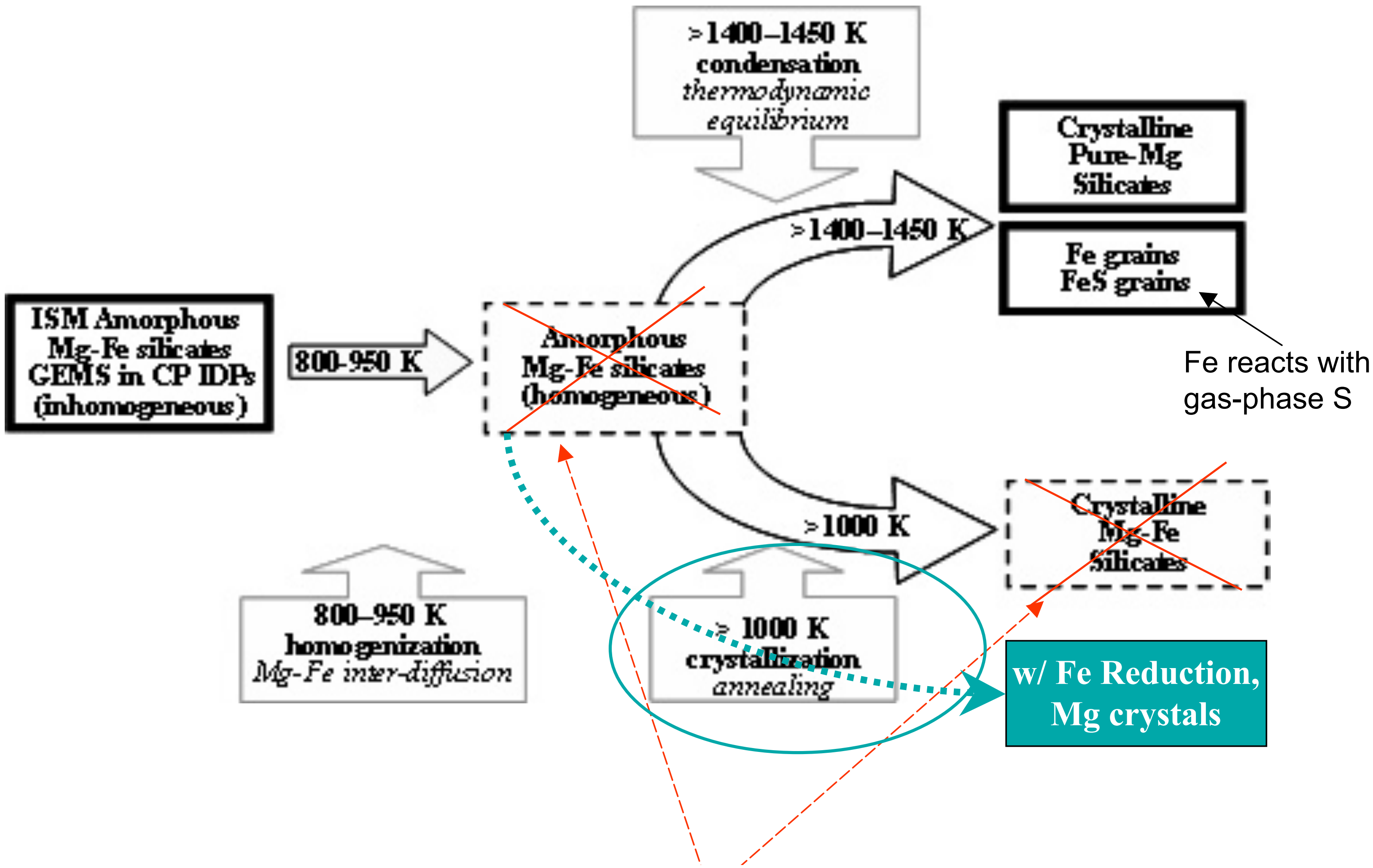


Annealing Mechanisms

- Accretion heating (< 2 AU, mass accretion rate 10^{-7} M_o yr^{-1})
- **Transient mechanisms** that can act over larger disk volumes than accretion
- Shocks
  - Gravitational instabilities in ~10 AU region (Harker & Desch 2002)
  - X-Ray Flares R< 80AU (PPV poster by Nakamoto & Miura)
- Annealing of Mg-pure amorphous grains produces Mg-pure crystalline grains (Brucato et al. 2002; Fabian et al. 2000) [100% efficient]
- Annealing of Fe-containing GEMS produces moderately Fe-rich olivine crystals (Brownlee et al. 2005) [Mg-Fe-crystals rarer in CP IDPs & comets]
- Rapid annealing of Fe-pure amorphous grains produces Fe-pure crystalline grains [Fe-crystals not seen in comets & CP IDPs]

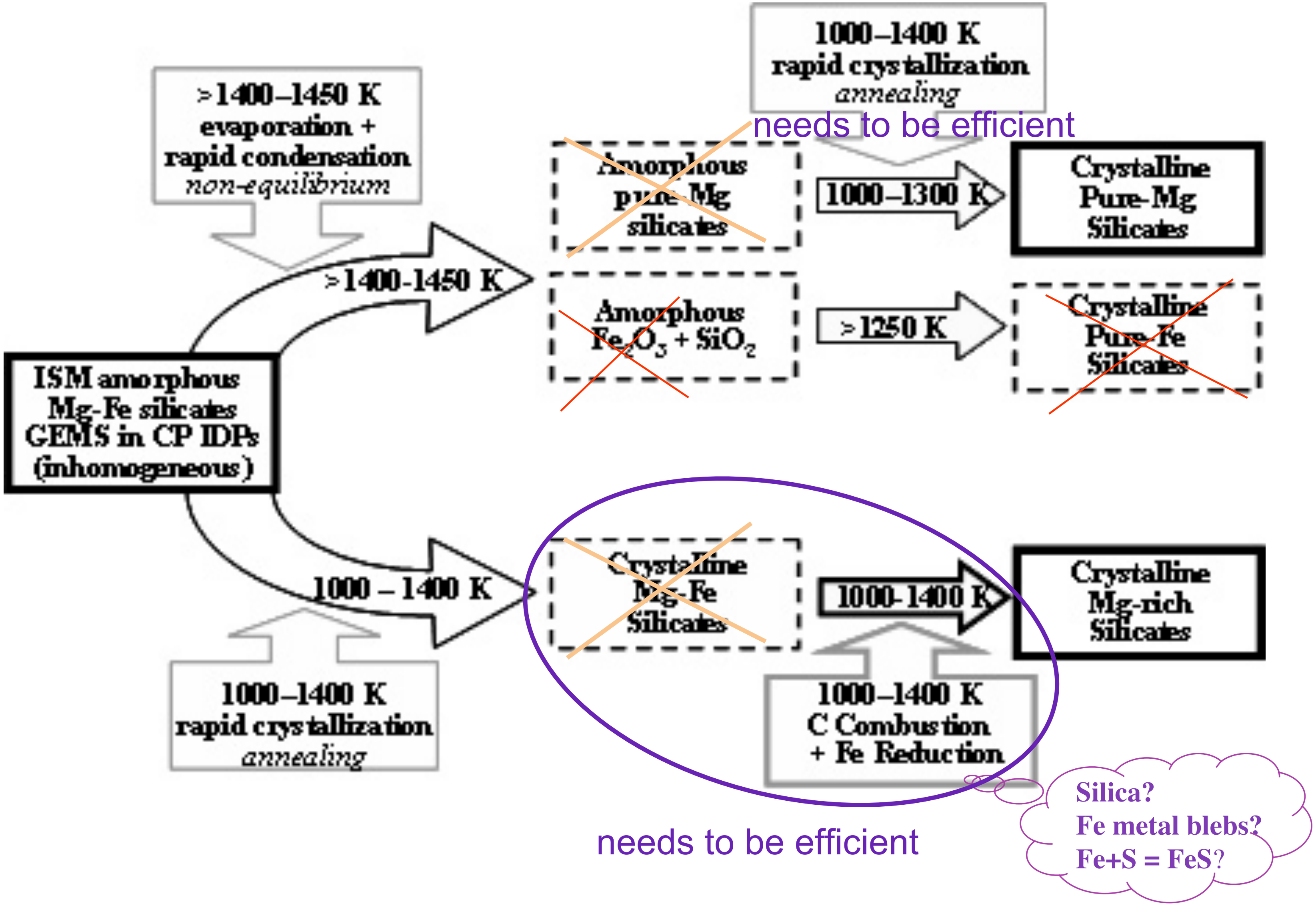
  [Caution: Nuth et al. produce Fe_2O_3 and SiO_2 that don't anneal to Fe-rich crystalline olivine, but Nuth et al. calls these products crys. Fe-silicates]
- **When annealing abundant Mg-Fe amorphous silicates to Mg-rich crystals, we need a mechanism to get the Fe out amorphous silicates!**

Equilibrium (+ Radial Diffusion)

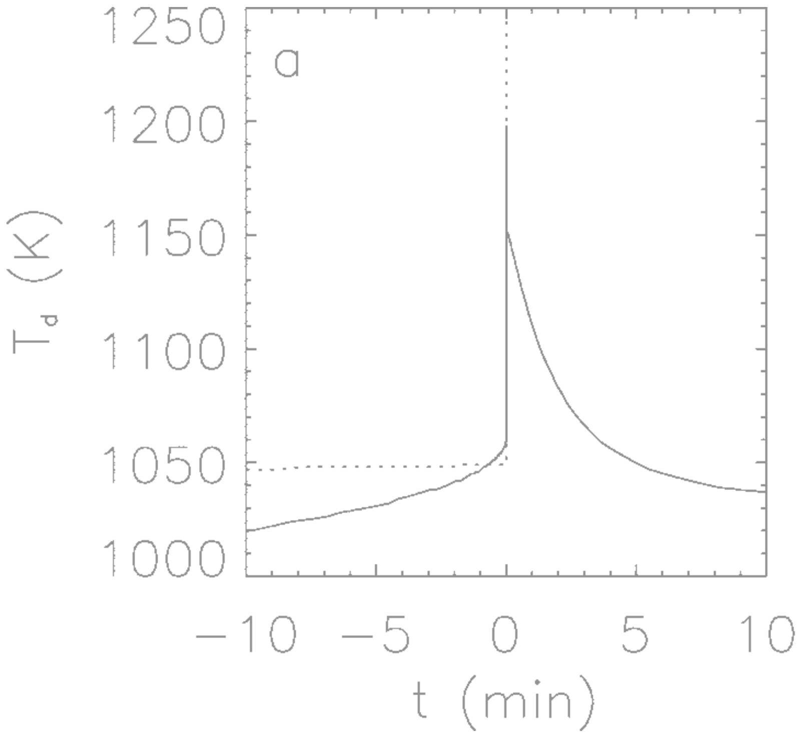


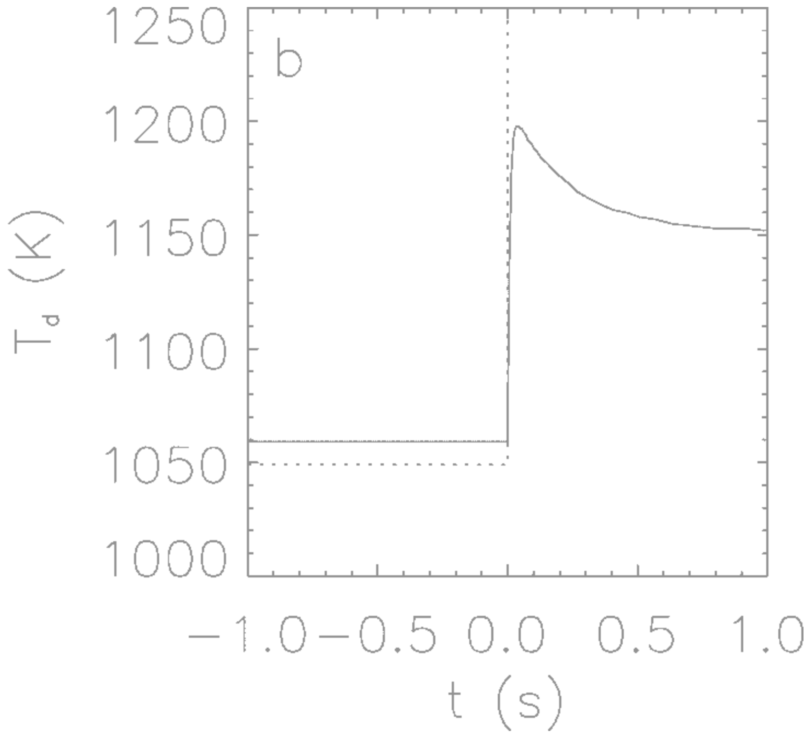
Not seen in comets or primitive enstatite chondrite matrices

Transient Heating



Shock speeds are sufficient in the 5-10 AU region to quickly anneal Mg-rich amorphous silicate grains



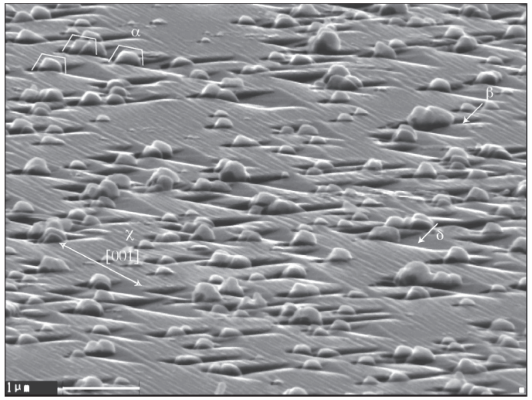


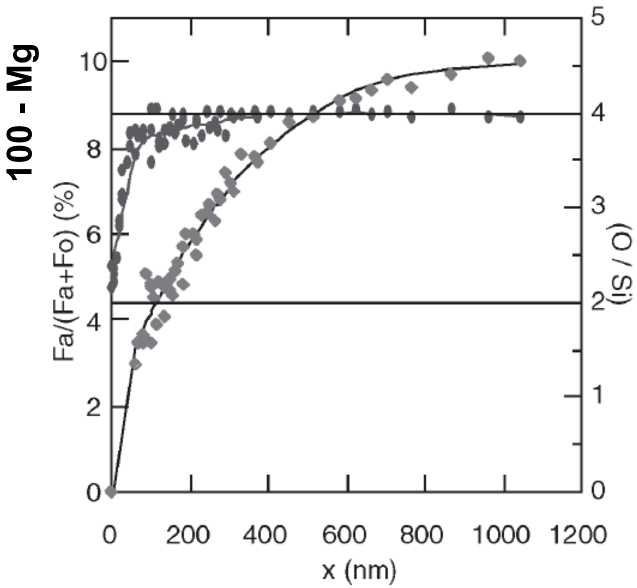
Plateau of higher temperatures (>1000K for 0.5-1 hr) may heat submicron radii grains long enough for **annealing & Fe reduction** to occur in the same shock -> ~100% efficient ? so few Mg-Fe crystals remain
so no Mg-rich amorphous remain

shock model Harker & Desch 2002, concept discussed in Wooden et al. 2006 PPV

Fe Reduction Experiments: Fe reduction can occur for grains in solar nebula gas because oxygen fugacity [fO_2] is low enough

$$Fe_2SiO_{4\ \text{in olivine}} + 2C_{\text{graphite}} = 2Fe_{\text{in metal}} + SiO_{2\ \text{amorphous}} + 2CO_{\text{in gas}}$$





Heating Mg-rich olivine on a carbon substrate forms Fe-metal blebs on surface, increasing Mg-content and leaving silica-rich surface layer.

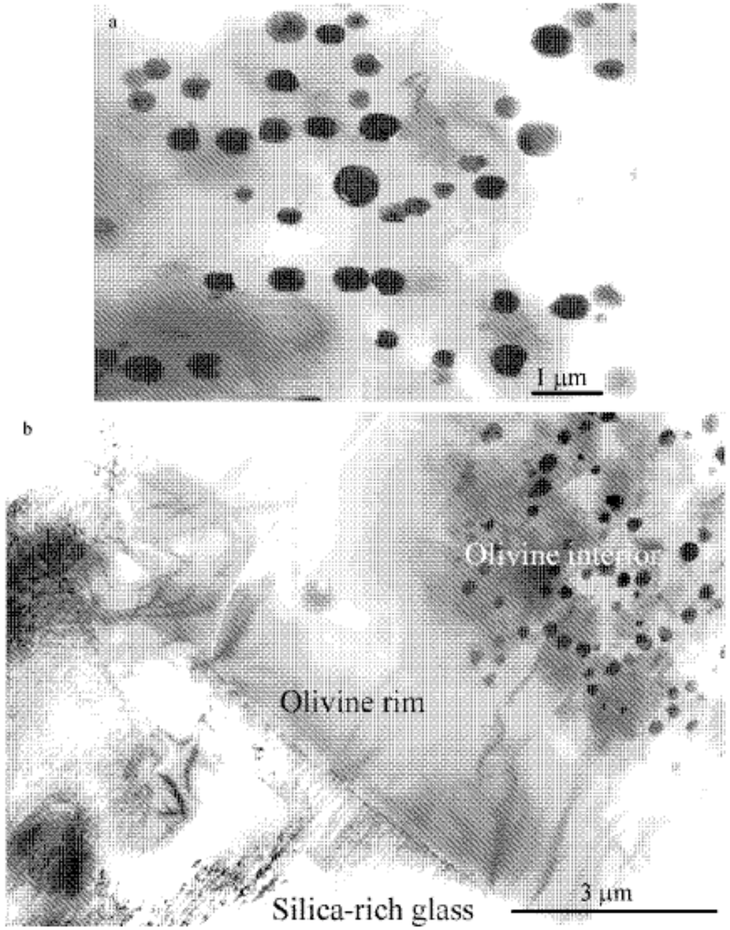
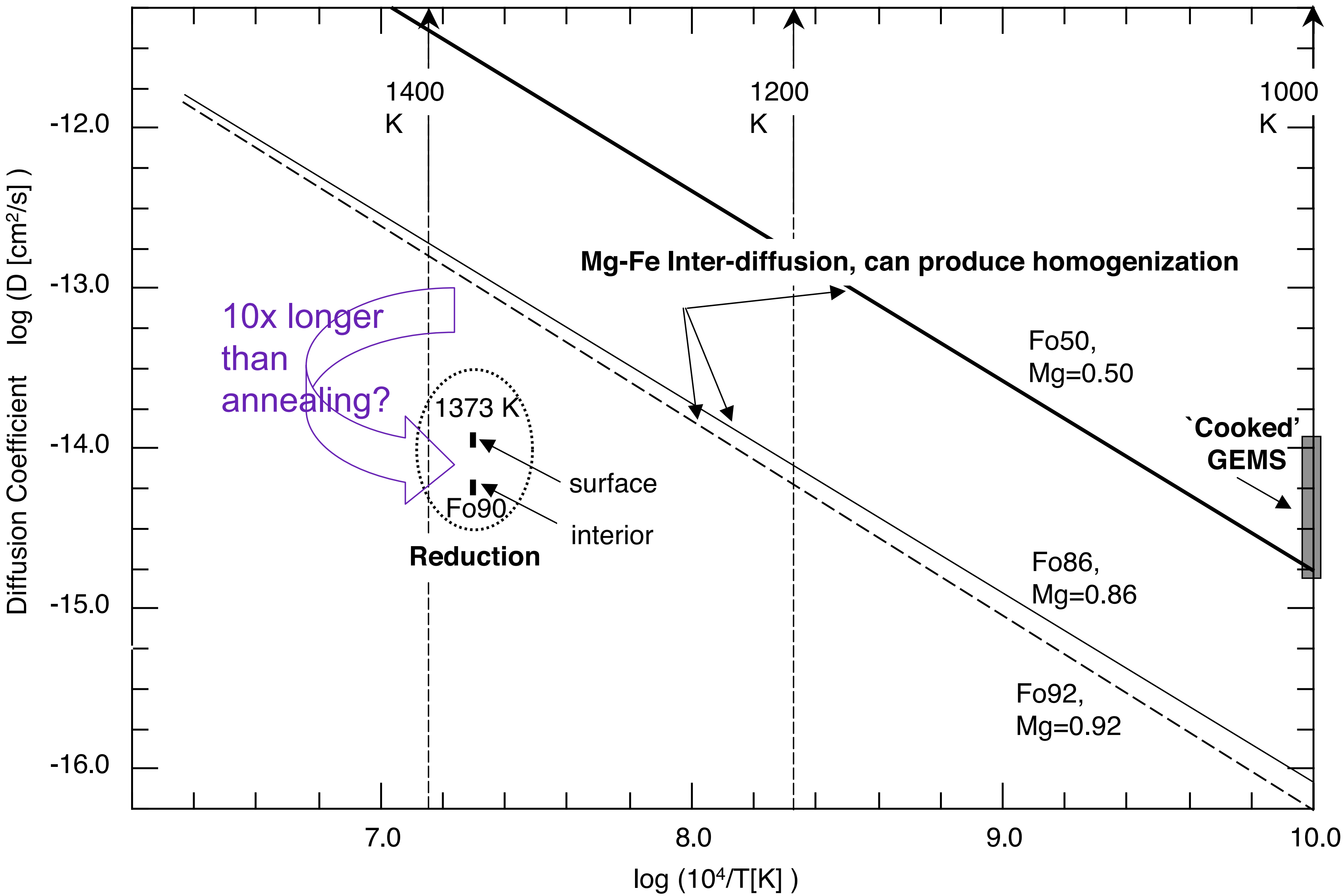


Fig. 7. TEM bright field micrographs, R100 sample: a) general view of a dusty area from an experimentally reduced San Carlos Fa16 olivine. Note the preferential orientation of the metal blebs in the olivine matrix; b) edge of an olivine grain. The rim is free of metallic precipitates. The adjacent phases to the olivine consists now of a dendrite-glass intergrowth; see text for explanation.

Lemelle et al. 2001, Amer. Mineralogist, 86, 47

Leroux et al. 2003, MPS 38, Nr1, 81-94

Reduction of Fe out of Olivine occurs at Mg-Fe Interdiffusion rates, **~10x slower** than rates for annealing of **pure-Mg** amorphous olivine to pure-Mg crystalline olivine



Wooden etal 2006 PPV

A&A 448, L1–L4 (2006)
DOI: 10.1051/0004-6361:200600002

Astronomy & Astrophysics

Starting Material: $\mathbf{Mg_{1.8}\ Fe_{0.19}\ Ni_{0.01}\ SiO_4}$

Mg/(Mg+Fe) =0.9

The origin of GEMS in IDPs as deduced from microstructural evolution of amorphous silicates with annealing

C. Davoisne[1], Z. Djouadi[2], H. Leroux[1], L. d'Hendecourt[2], A. Jones[2], and D. Deboffle[2]

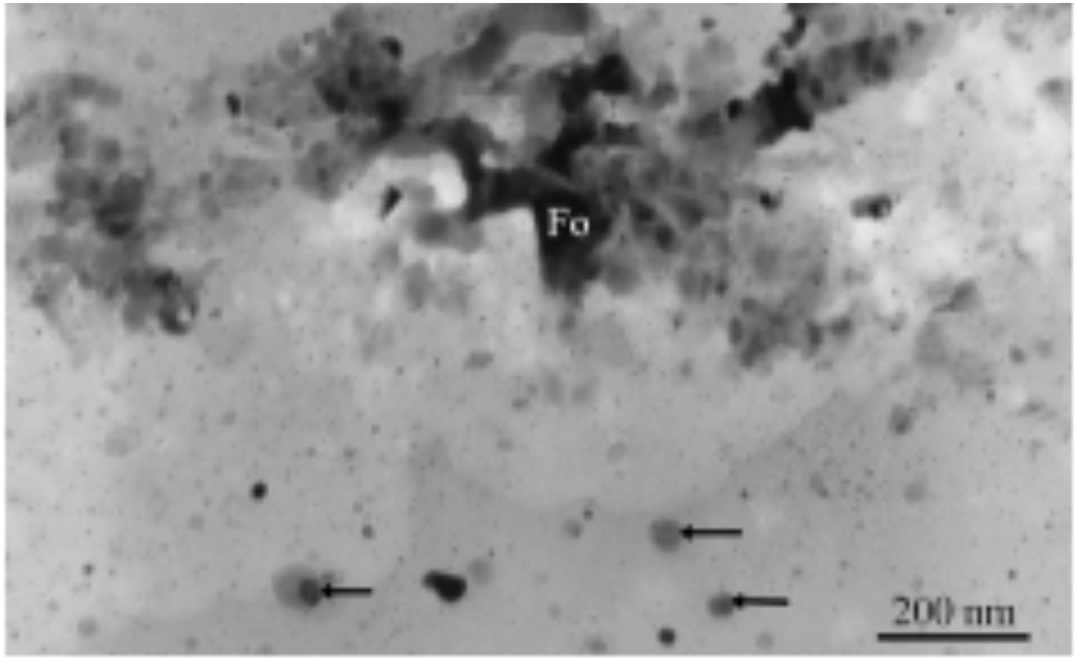


Fig. 2. TEM micrograph of sample annealed at 970 K (55 h) showing a forsterite crystal (Fo) embedded in a amorphous matrix. Note the dentritic structure at the edge of the grains. Some metal particles are also present in the amorphous phase (some of them are arrowed).

ing annealing was 10^{-10} bar. The very low oxygen partial pressure ($<10^{-20}$ bar) necessary for the reduction reaction to proceed is probably due to carbon-rich contaminants coming from the pumping system, which consumes oxygen by the reaction $C + 1/2\ O_2 \longleftrightarrow CO$ and thus induces metal formation

the samples before their total crystallization. The main characteristic of all the samples annealed (at 10^{-10} bar and without O_2 circulation) is the presence of widespread iron-nickel nano-particles (Fig. 1) randomly distributed, 2–50 nm in size, for which the compositions are highly variable, from 3 to 50% Ni. The amorphous phase which encloses the metallic globules is free of Fe. This microstructure and microanalyses clearly show that iron, initially in form of FeO, has segregated from the amorphous phase in the form of metallic precipitates. Despite the presence of metallic precipitates, the average composition (amorphous silicate + metallic nano-particules) is found strongly depleted in Fe. A moderate loss of Mg is also observed.

GEMS have silica-rich subgrains and FeS-rich subgrains: a consequence of reduction of Fe out of the grain under solar nebula (low) oxygen fugacity conditions and FeS formation??

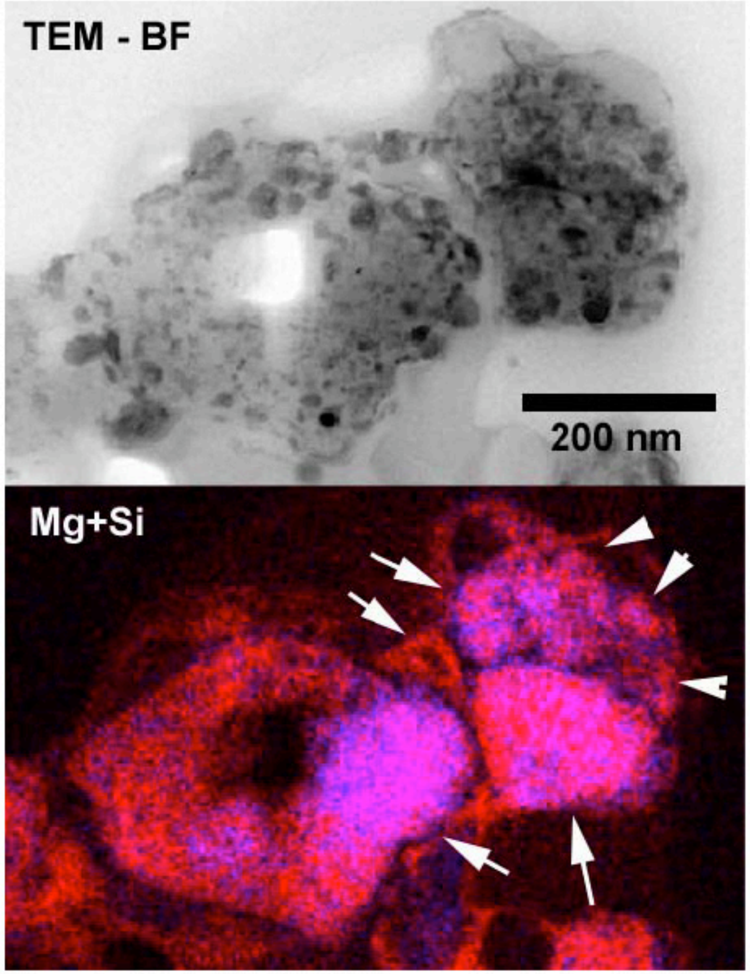


Figure 1. A brightfield STEM image of a cluster of GEMS in IDP L2011B10 (top) and the corresponding Mg+Si distribution map extracted from the EDX spectrum image (bottom). The white arrows indicate the numerous compositionally distinct subgrains that comprise the GEMS aggregate grain.

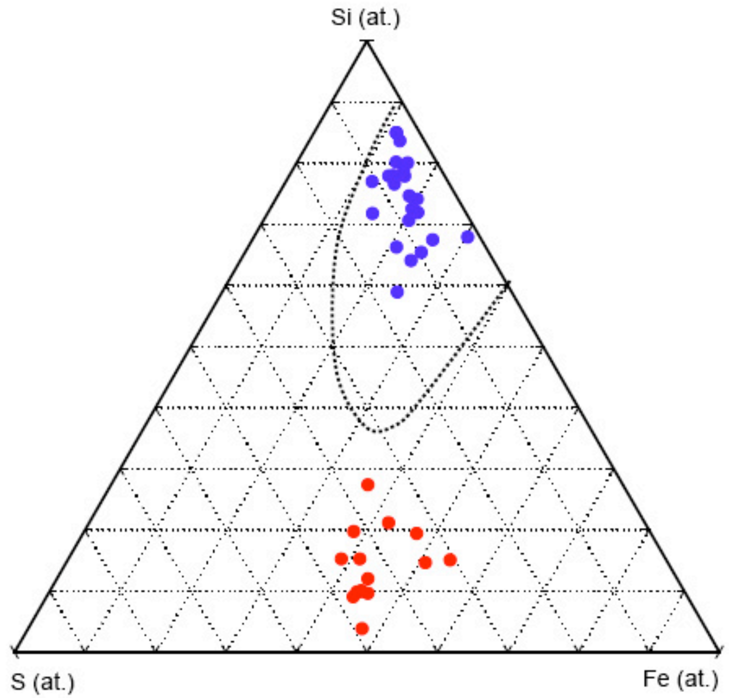


Figure 2. Ternary plot of measured Fe, Si, and S atomic abundances in GEMS subgrains showing the silica-rich (blue) and FeS-rich (red) subgrain compositions. The dashed line defines a field that encompasses previous bulk GEMS grains analyses [3, 8].

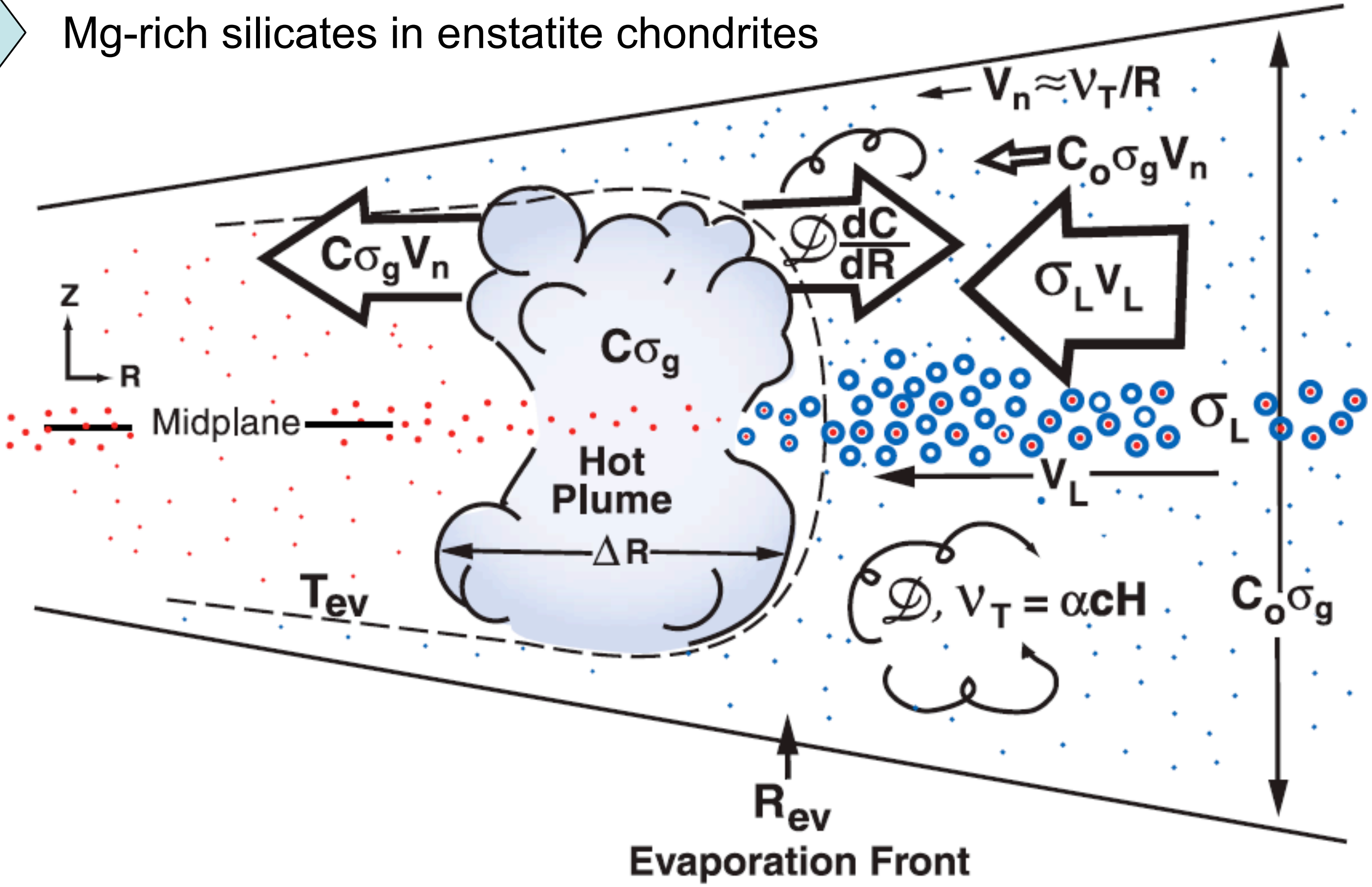
Keller, Messenger, Christoffersen 2005, LPS 36, 2088

Inward Migration of Icy Cometesimals/particles can Raise Oxygen Fugacity by water vaporization -> water dissociation -> forms O_2 -> raises $f[O_2]$

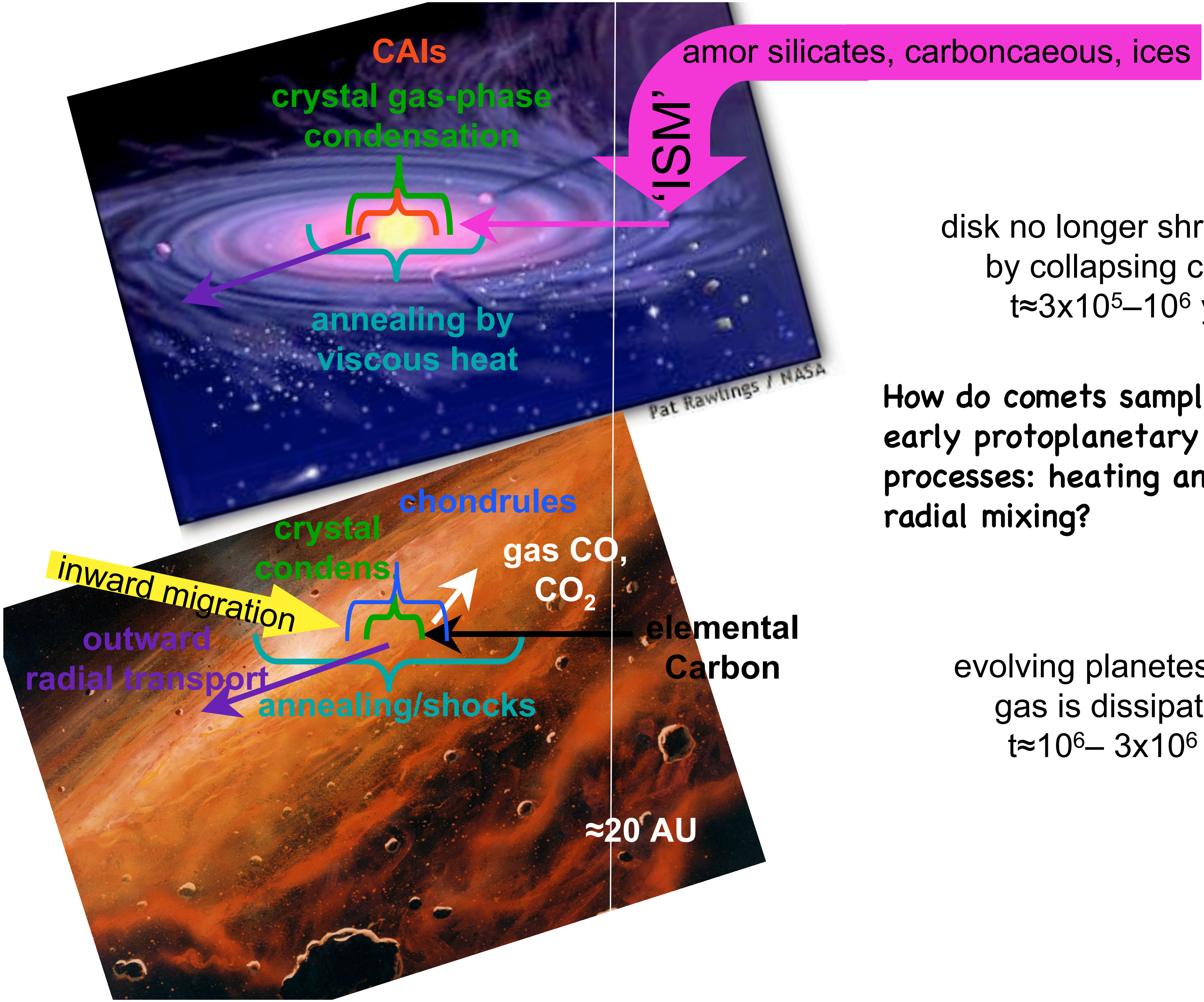
Fe-rich silicate chondrule rim formation (but small percentage of volume)

Inward Migration of Carbon-Rich Cometesimals/particles can Lower Oxygen Fugacity by C combustion to CO, CO2 -> lowers $f[O_2]$

Mg-rich silicates in enstatite chondrites



Cuzzi & Zahnle (2004)



disk no longer shrouded by collapsing core
$t \approx 3x10^5 – 10^6$ yr

How do comets sample early protoplanetary disk processes: heating and radial mixing?

evolving planetesimals
gas is dissipating
$t \approx 10^6 – 3x10^6$ yr

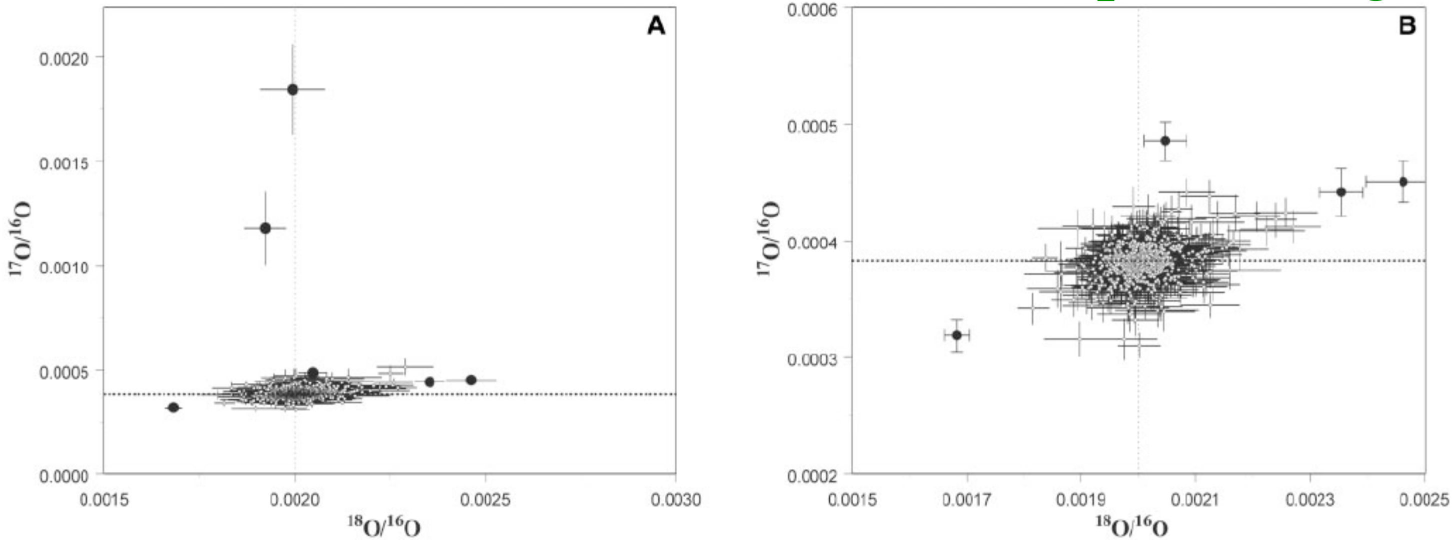
Some Controversial Topics...

New JFC Paradigm: Crystals are Skin-Deep

- Deep Impact-induced ejecta has silicate crystals (Spitzer, Gemini, Subaru).
- Post-impact (by <1 rot. period) has crystals (VLT).
- Pre- and post-impact dust has no crystals, dominated by amorphous silicate grains (Gemini).
- Dust in coma in May 2006 (activity maximum) has submicron amorphous silicate grains, no crystals (Keck).
- 73P-C/SW-3 and 73P-B/SW-3 have crystals (broken up 2 orbits ago, and breaking up April '06) (Gemini)
- TREND: JF comet materials from "below their mantles" possess silicate crystals.
- DIRECTION: community effort to study mineralogy and organic volatility versus r_h in select JF and OC comets

New Paradigm?: ISM crystals/GEMS rare <1%

How extreme/efficient is solar nebula processing?



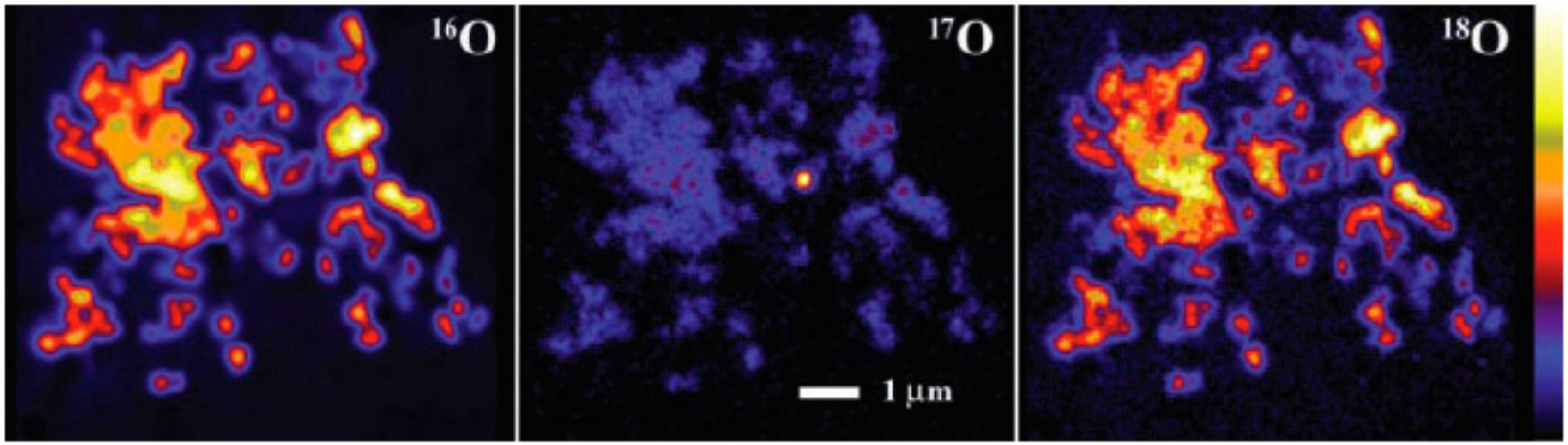
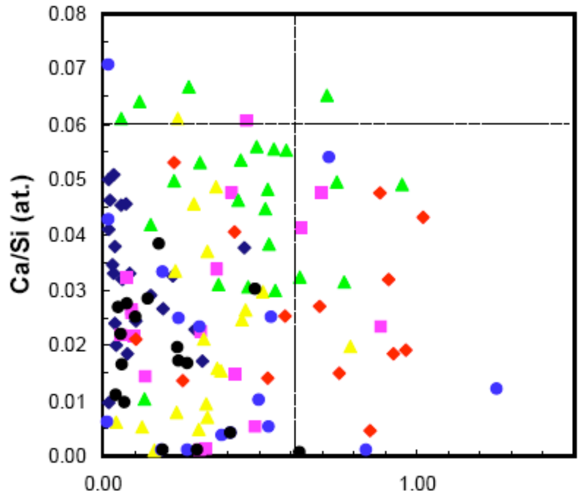


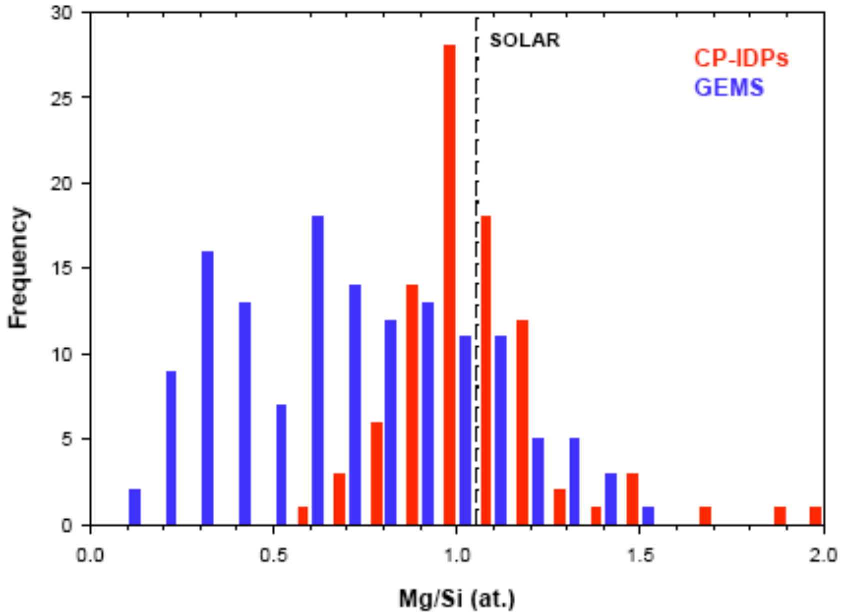
Fig. 2. Oxygen isotopic images of a slice of IDP L2005 C13. A presolar grain with a large ^{17}O excess can be clearly seen in the ^{17}O image.

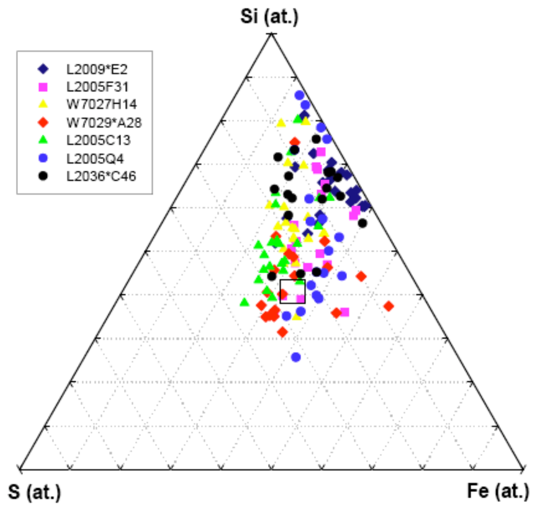
Messenger et al. 2003

New Annealing Paradigm?: 60-80% of GEMS are systematically sub-chondritic in S, Mg, Ca, Fe compared to Si

Keller & Messenger (2004) LPS XXXV 1985







Diane asks: Were most (60-80%) of amorphous silicates annealed by high fluxes (10^4-10^5 x today's Sun) of low Energy *solar* cosmic rays? [cosmic rays-Feigelson et al.]

Amorphous vs Crystalline Water Ice

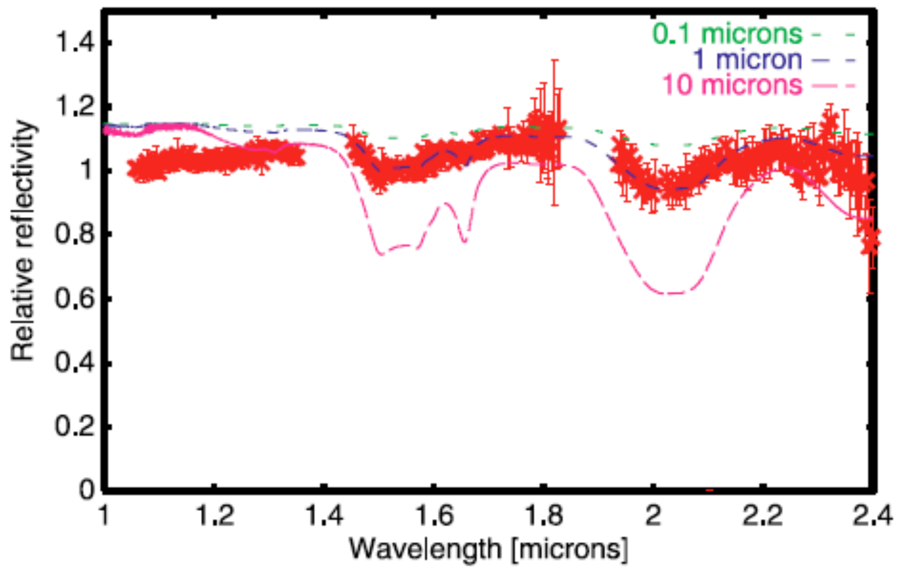


FIG. 1.—Spectrum of comet C/2002 T7 (LINEAR) along with synthesized spectra for pure H_2O crystalline icy grains (0.1, 1.0, and 10.0 μm, in diameter). The absorption by H_2O ice is clearly shown in the cometary spectrum. However, the agreement between the cometary spectrum and the pure H_2O spectrum is not good in the *J* band.

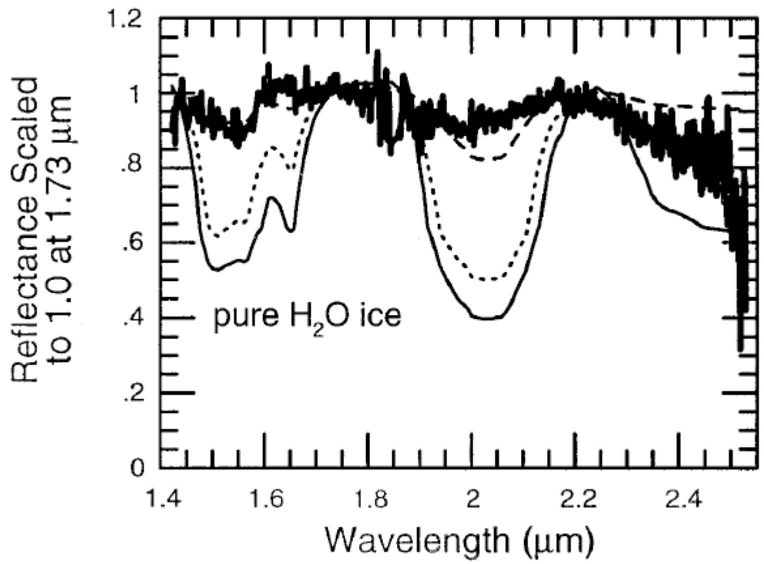
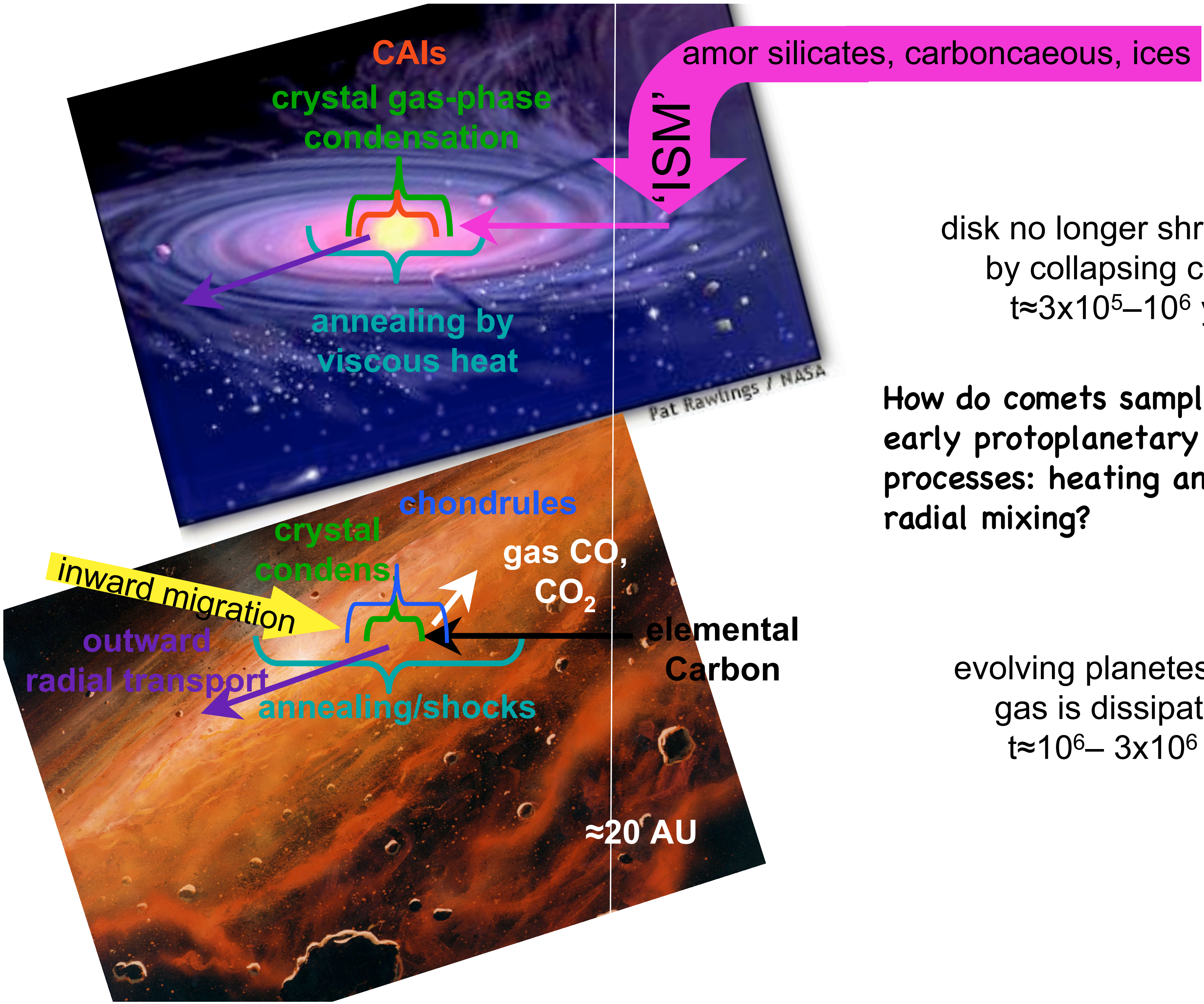


FIG. 3. Comet Hale-Bopp data (heavy solid line) compared with the reflectance calculated for water ice having grain diameters of 1 μm (dashed line), 5 μm (dotted line), and 10 μm (thin solid line).



disk no longer shrouded
by collapsing core
$t \approx 3x10^5 – 10^6$ yr

How do comets sample early protoplanetary disk processes: heating and radial mixing?

evolving planetesimals
gas is dissipating
$t \approx 10^6 – 3x10^6$ yr

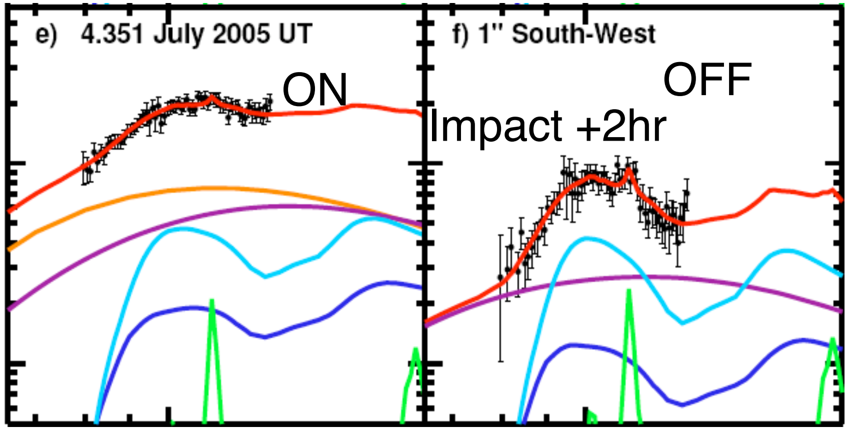
Interpretation of DI Dust...

Wooden, Woodward, Harker 2007

DI as a World Observatory Event

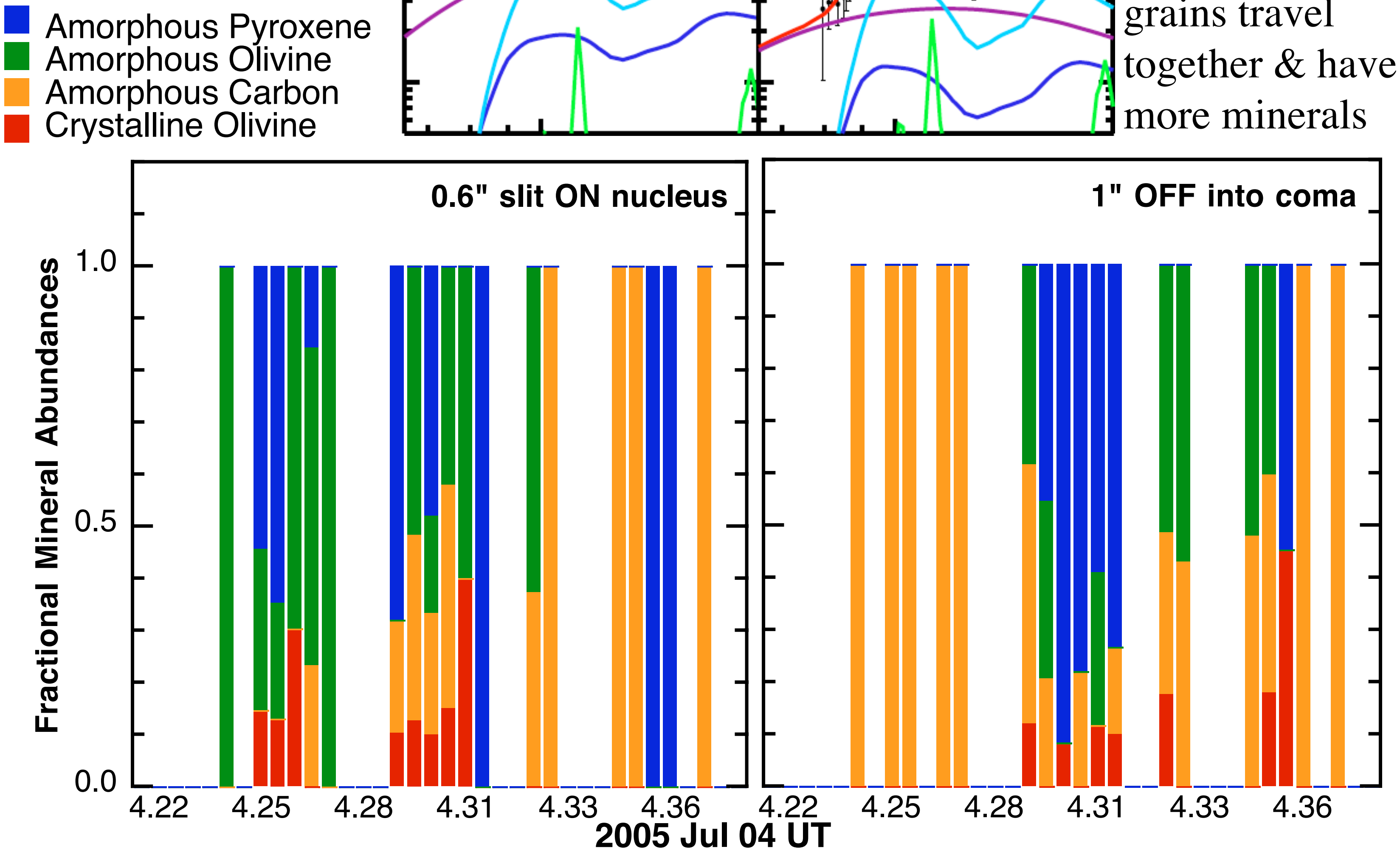
Brussels Mtg (submitted)

9P/Tempel 1 Review of Gemini results ...



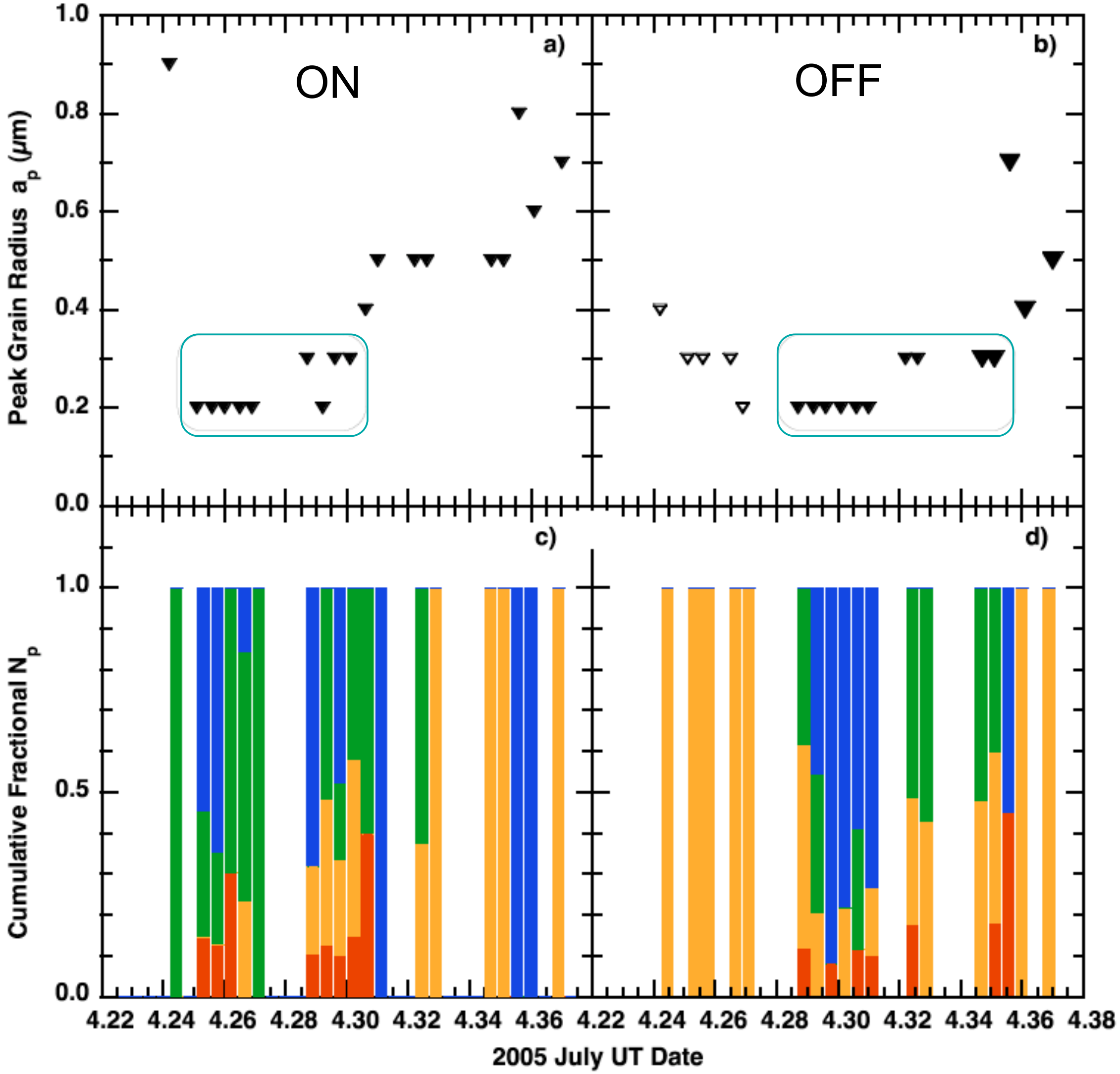
1st Amorphous carbon in "OFF"

2nd submicron grains travel together & have more minerals



Harker, Woodward, Wooden (2006) Icarus, accepted.

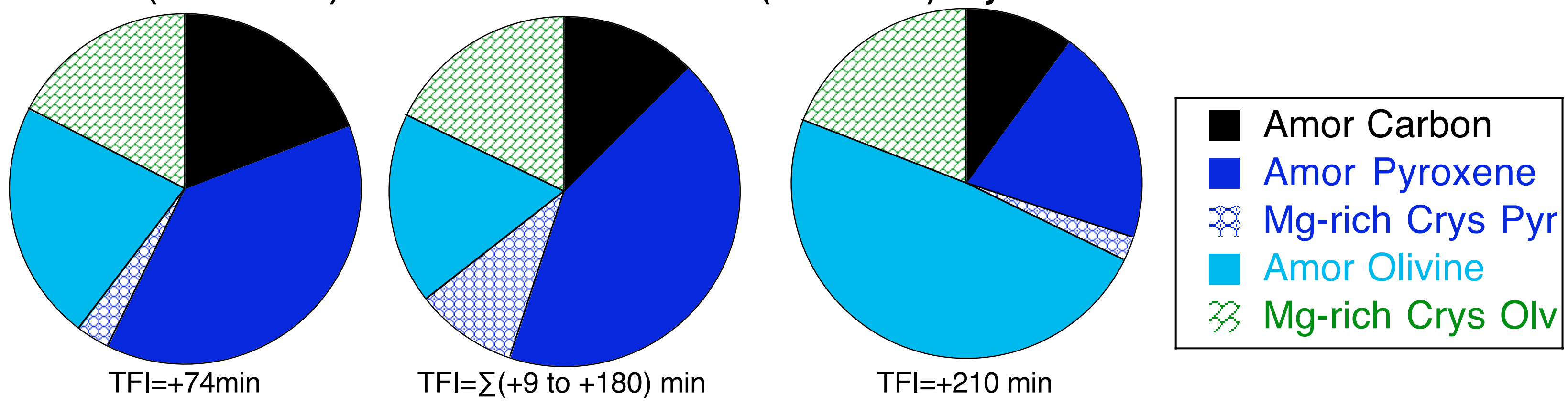
Smallest grains are ON nucleus and sustained for 30 min, but takes time (>30 min) for these smallest grains to reach maximum 1" OFF into coma
Grain size dist with smallest grains have 4 minerals or are ensembles of 4 minerals.
Larger grains persist longer ON and OFF (move slower), and have 1 or 2 minerals.



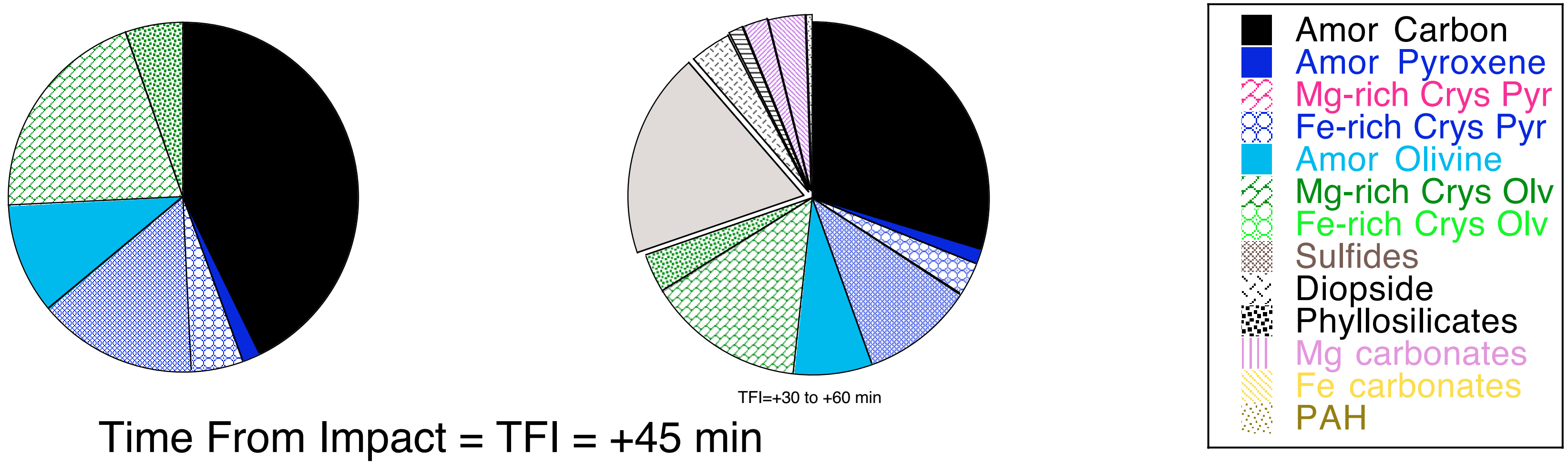
Deep Impact Ejecta-Coma: Comparison of Observation-Modeling Results

0.1–1 μm Portion of Grain Size Distribution Relative Mass Fraction

(GEMINI) On-Nucleus (Subaru) Ejecta-Coma



Grain Surface-Area Weighted Mass Fraction (Spitzer)
Only for Minerals Constrainable with 10μm and with 5–37μm



Time From Impact = TFI = +45 min

Deep Impact Dust Properties - Summary

- The nuclear subsurface appears to have an inhomogeneous mineralogy yet contains a volume *or pocket* of submicron grains of relatively homogeneous yet complex mineralogy. In contrast, the surface appears to be dominated by amorphous carbon.
- The effect of gas drag on the grains is to size sort the grains in the coma as a function time from impact (TFI).
- Silicate crystals travel out with the smallest grains and therefore, by velocity-association, crystals are small. However, from TFI=+0.5~hr (Gemini and Subaru) to TFI=+10~hr (Spitzer) the crystalline fraction does not change significantly as the smaller (0.2--1μm) grains clear out and larger grains travel through the beam. Therefore, crystals are not necessarily only associated with the smallest grains (0.2 μm). Future analyses of the Spitzer spectra may yield further results on the relationship between the crystalline fraction and the grain size.

DI V- Possible Reasons the Crystalline Silicates Not Seen in the Normal Coma (versus DI)

- Grain size Distribution does not extend to small enough grain sizes.
- Grain size Distribution slope is too shallow so smallest grains are not dominant enough.
- Crystalline resonances are diminished in contrast (to the point of non-detection) if the crystals are contained within larger aggregate grains.
- The crystals comprise only the smallest grains in the size distribution, which means crystals dominate the grains' surface area but are only a small fraction of the total mass. The mass fraction of crystals is too small for crystals to be detected in the normal coma.
- Normal activity is from mantles (outer layers a few cm to a m deep) that are devoid of crystals. So mantles have a specific composition and mantles are retained. From mantles, crystals are lost; or, in mantles crystals are destroyed.
- The nucleus is inhomogeneous on smaller scales than the DI impact-crater; where DI impacted 9P, the surface is rich in amorphous carbon and rarified in crystals and the subsurface contains zones of amorphous pyroxene and crystals, and amorphous carbon and amorphous olivine.

Look at the Explanations for Differences - A

- Grain size Distribution does not extend to small enough grain sizes.
  NOT TRUE ap=0.3μm May 25, 0.6μm May 17

- Grain size Distribution slope is too shallow so smallest grains are not dominant enough.
  Implies: The crystalline fraction f_{crys} is grain size-dependent and the size distributions for normal comae were devoid of these smallest grains. NOT TRUE for $a_p \leq 1\mu$m grains; investigate for $a_p > 1\mu$m with Spitzer

- Crystals are hidden within larger aggregates.
  lab spectra of IDPs shows $f_{crys} < 0.17$ then crystals may be hidden
  Hale-Bopp DDA computations show $f_{crys} = 0.55$ for 0.1--5μm size particles
  same as for discrete mineral model

- Too Small a total Mass of dust to see Submicron Grains?
  Same Mass of dust in inner coma measured on 2 dates, so :
  Mdust(DI,+ 0.5 to +3.5hr) ≈ Mdust(9P on 17 May, single measurement)

Look at the Explanations for Differences - B

- Activity from Mantles Devoid of Crystals

  Implies (1) in Mantles, crystals are destroyed and (2) Mantles are retained

(1) In Mantles, Crystals are Destroyed

Low Energy Solar Cosmic Rays:

For the young Sun (0–10^6 yr), flares probably produce ~10^5 times more solar cosmic rays (Glassgold et al. 2005; Feigelson, Garmire, & Pravdo 2002 ApJ, 584, 911). If each cometesimal in the layered pile has an amorphous silicate skin (rime), then this implies very rapid amorphization rates at the time of accretion of the outer layers.

Problem: Low Energy Cosmic Rays penetrate <100 μm depth

Need: Gardening by micrometeorite impacts or dust sputtering

(2) Irradiation of ices creates porous organic residues that “shrink” as sublimation occurs below their surfaces

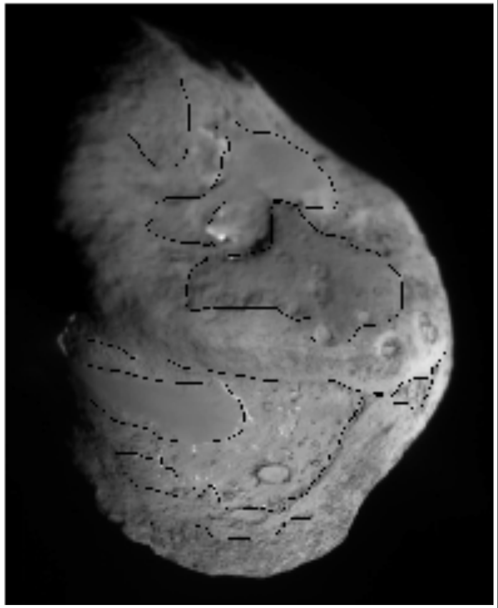
(3) Challenge: 9P water ice subliming from 3 cm below surface

Qdust implies loss of 3cm/ROTATION PERIOD (41hr) over surface

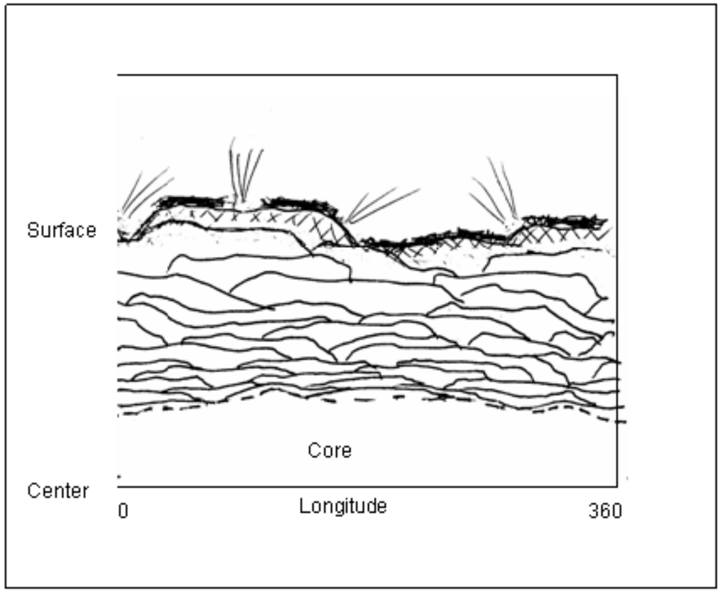
or 30cm in 10% of the surface

Look at the Explanations for Differences - C

- Nuclear Inhomogeneities on Smaller Size Scales than Topography, on depth scales smaller than 10m deep and 100m wide



(Belton et al. 2006, LPS 37, #1232)



TALPS OR LAYERED PILE MODEL

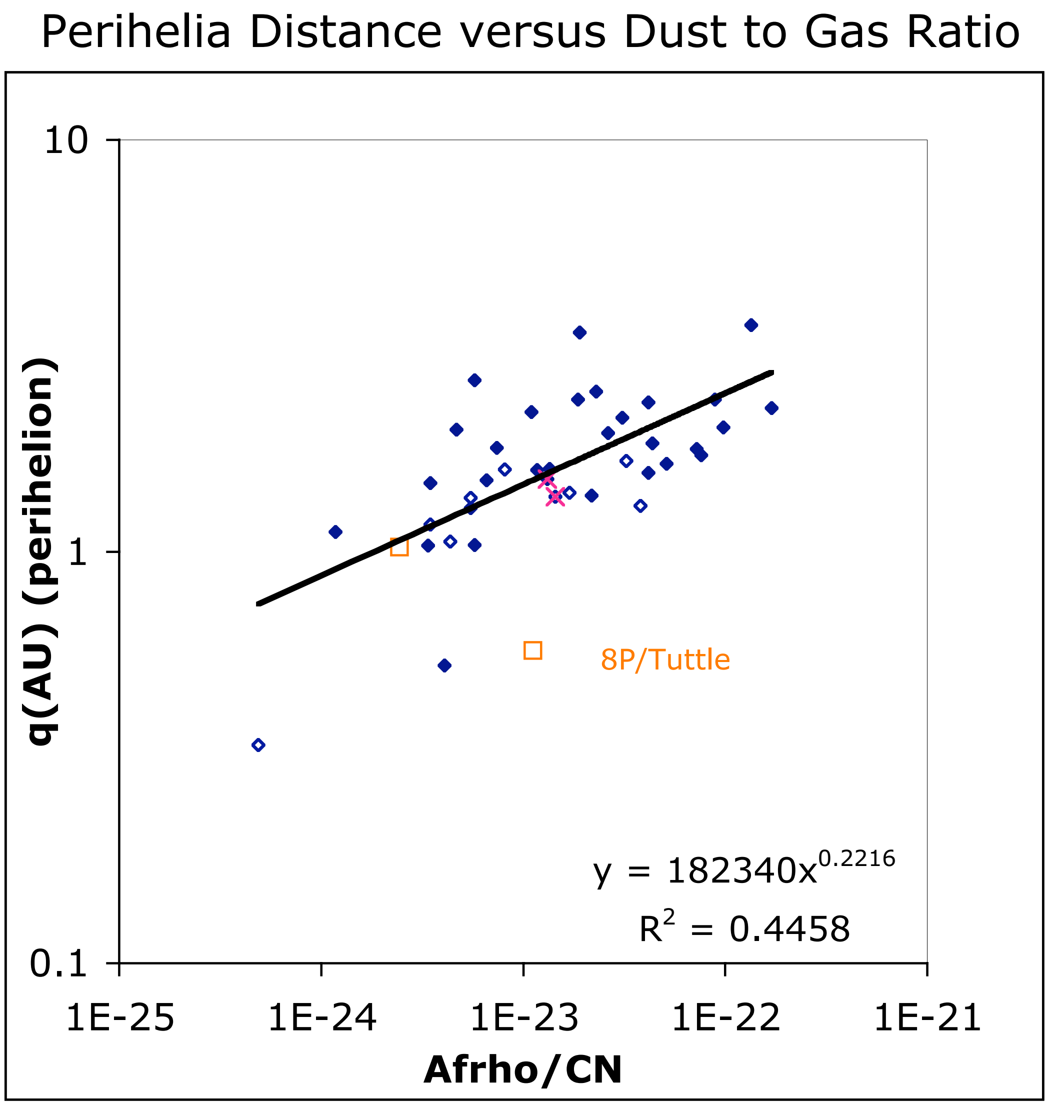
- the current surface topography is a result of the accumulation of layers of cometesimals
- the early layers are smaller because the modal size of the impacting aggregates is smaller
- the early layers are more compact because impact speeds are higher for smaller bodies
- the late-accumulation layers may be 50 m thick (390~m diameter cometesimal)
- perhaps 500 layers are on top of the nuclear `core'
- except for the surface layers, each layer experienced a mean exposure age of 5000--50,000 yr in the protoplanetary disk, if ~25 layers cover the surface at any particular time in the accumulation process
- probably a number of surface layers are already lost due to sublimation during previous orbits in the inner solar system
- Dust Results: accumulating layers are themselves inhomogeneous; inhomogeneities were preserved in collisions of cometesimals during the epochs of growth of nuclei.

Future Directions

Spitzer & Subaru: C/2006 Q1 (McNaught)

Subaru: Jupiter Family Comets

Rimes (somehow) regulate coma dust properties



Dust/gas Ratio declines for comets that come closer to the Sun (q_{AU})

Hypothesis: Rimes of comets that come closer to the Sun lack loose small (<few μm) grains that contribute to Afrho (following A' Hearn et al. 1995).

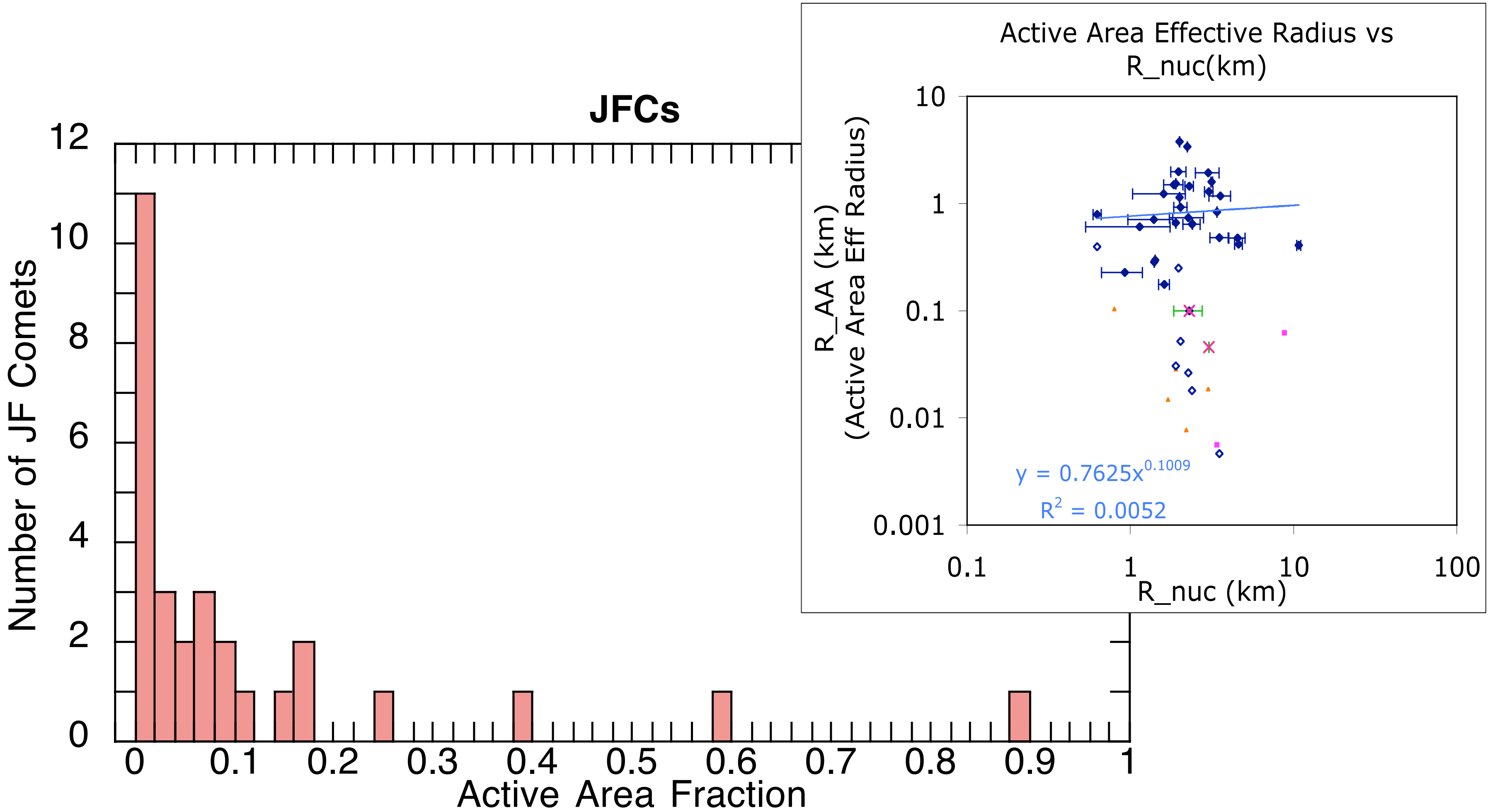
Lower Afrho means fewer smaller grains...

Are there fewer small grains

- due to preferential loss?
- due to preferential mantle trapping?
- due to some other mantle "mechanics"?

Are there actually fewer small grains? (add mid-IR to Afrho)

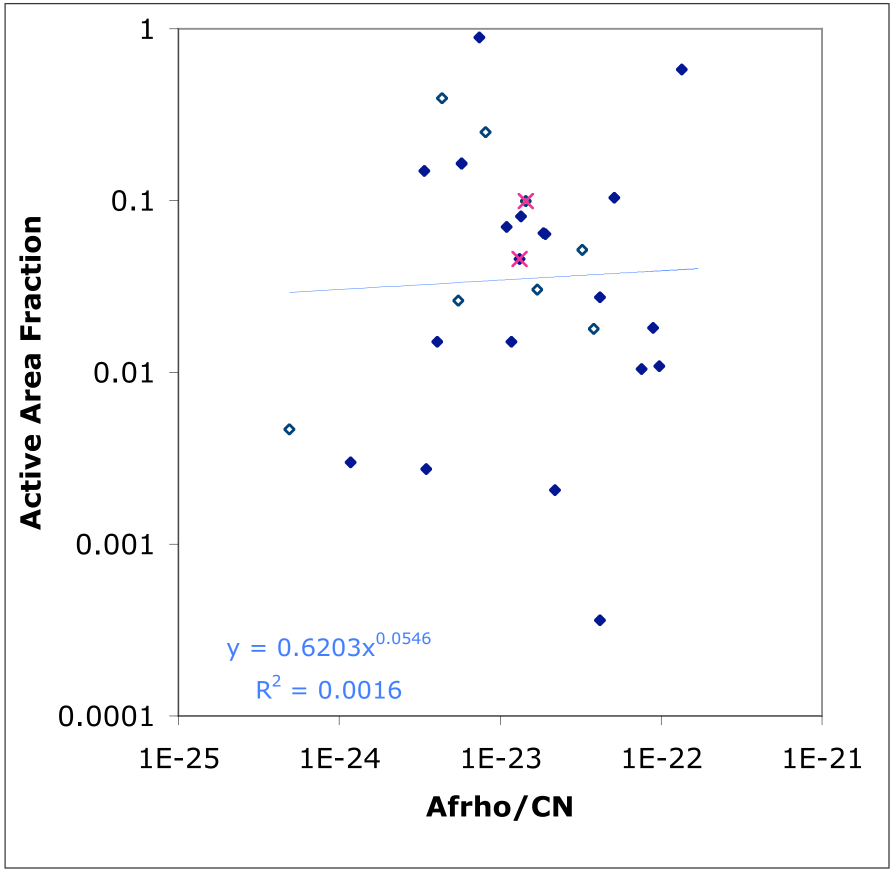
Rimes (somehow) regulate coma dust properties: ensemble of JFCs have small Active Area fractions



Active Areas [km^2] A'Hearn et al. 95; R_{nuc} Lamy et al. 05 Comets II

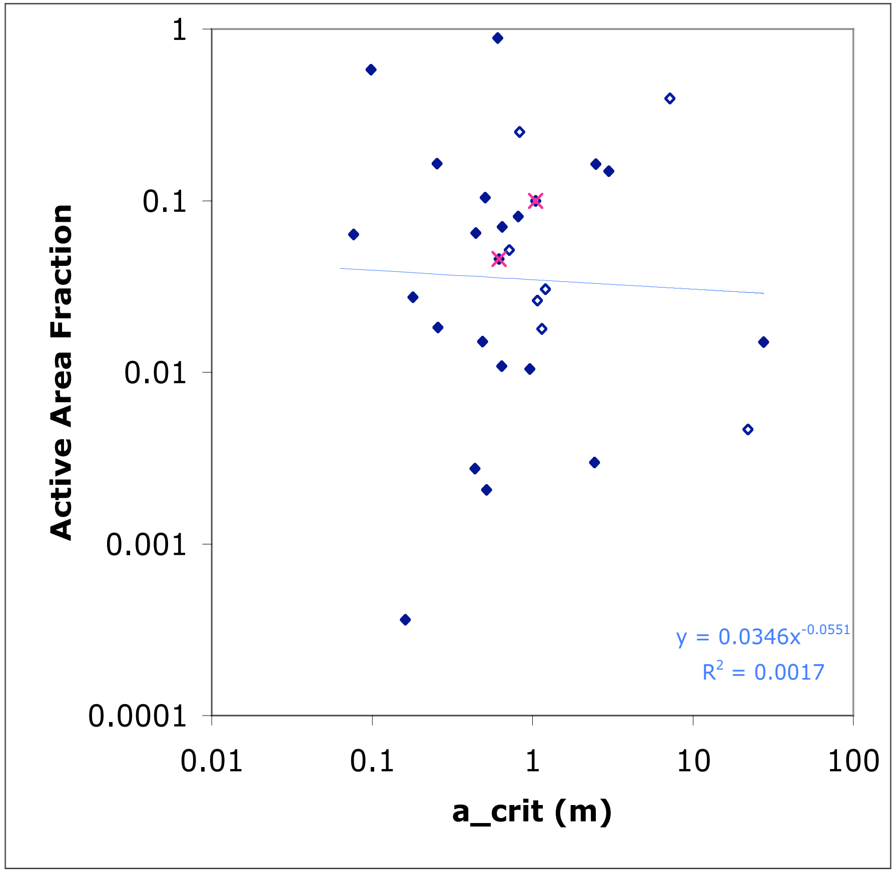
Active Area fraction (AAf) not dependent on Dust/Gas Ratio nor critical grain radius a_{crit}

Active Area fraction is independent of Gas/Dust Ratio



No affect on AAf if more grains entrained by escaping gases

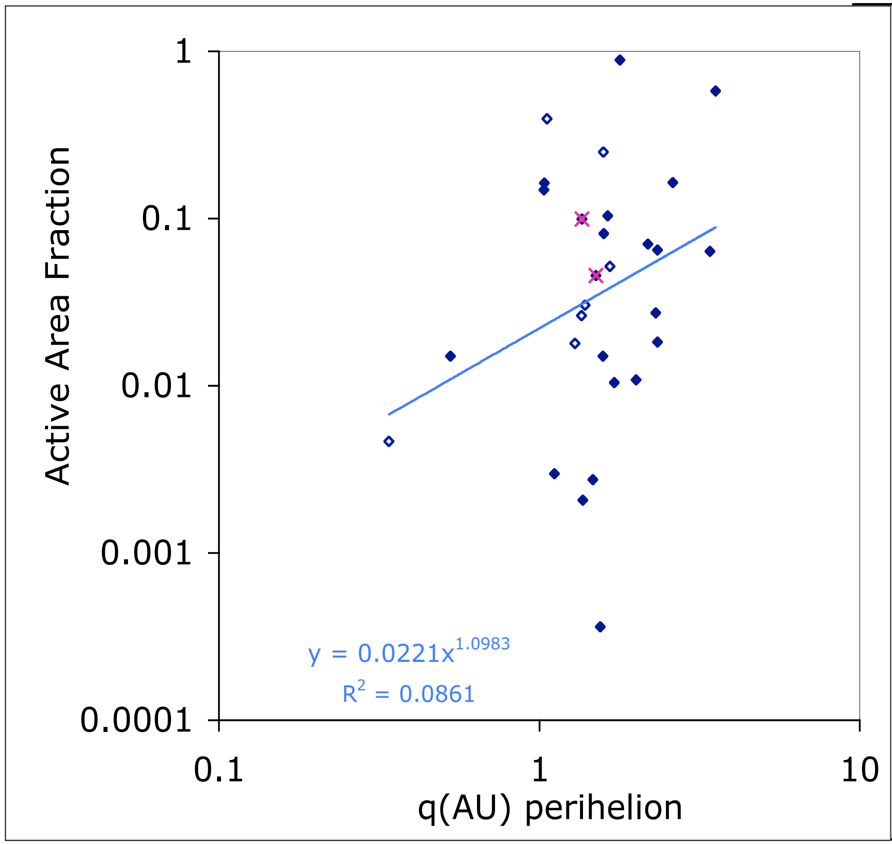
Active Area fraction is independent of grain sizes >a_{crit} retained against F_{drag}

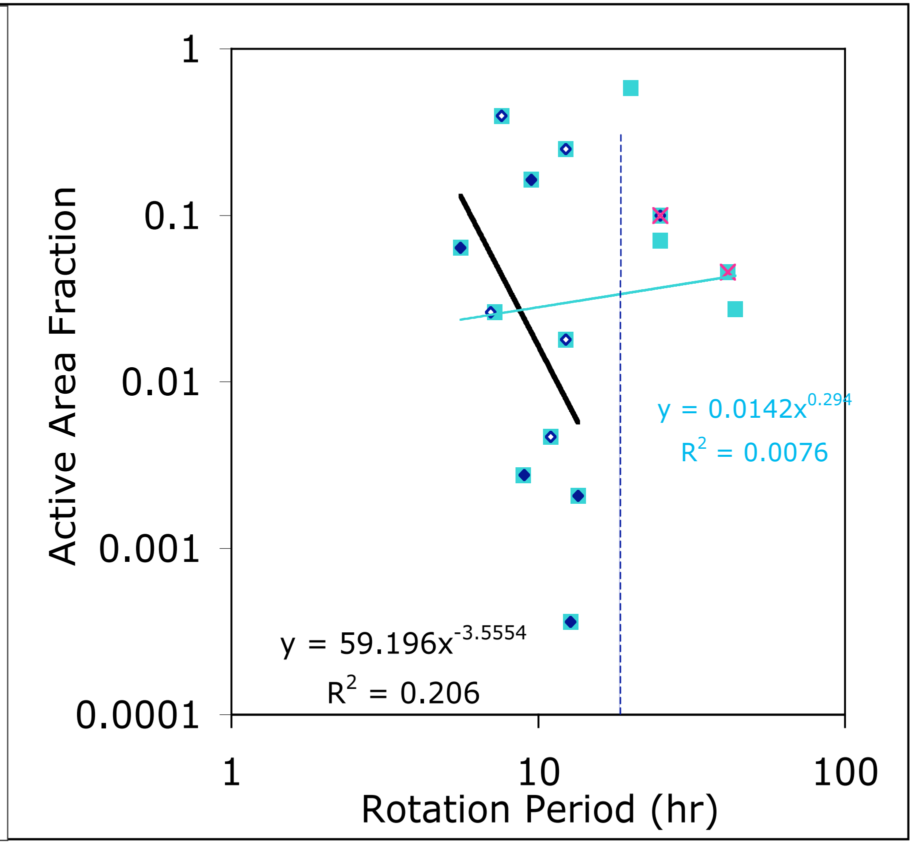


No affect on AAf if smaller grains are retained against F_{drag} (a_{crit} smaller)

Perhaps Active Area Fractions depend on P_{rot} for $P_{rot} < 20$ hr.

Nuclear Evolution Models predict Active Area fractions (AAf) are higher in comets that rotate more rapidly, because more uniform temperatures over P_{rot} prevent re-icing or 'sealing' at high latitudes (deSanctis et al. 1996). Comet 46P/Wirtanen may be an example.

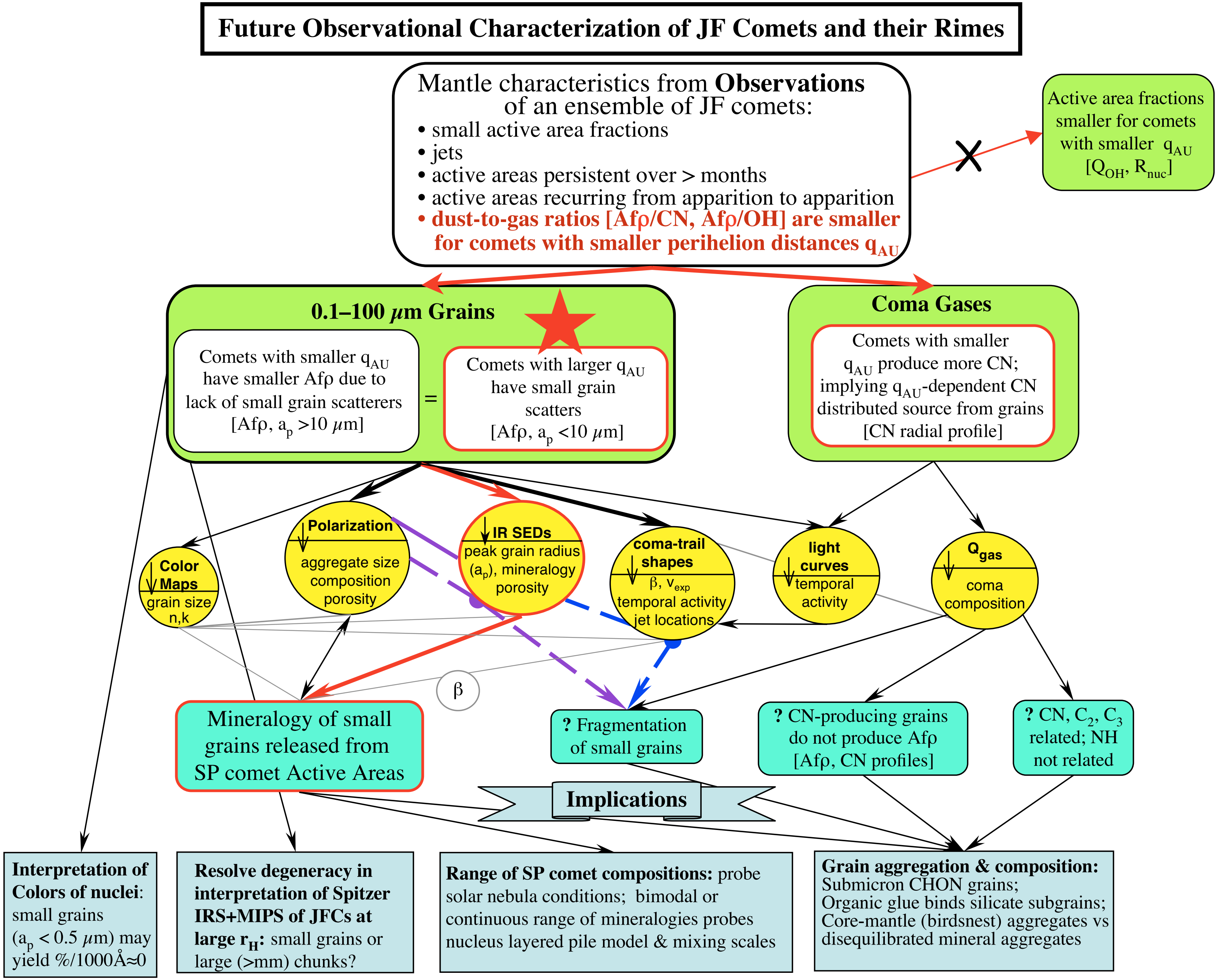




the next 3 years: 2P, 4P, 6P, 8P, 19P, 26P, 46P, 67P, 85P, 88P, 96P C/2006 Q1 (McNaught)

Comet Name		Perihelion Date (UT)	q (AU)	Q (AU)	P (yr)	log Afρ/CN	Active Area fraction	distant Rnuc (km)	Rotation period Prot (hr)	T-mag @ perih. (Vmag)
2P/Encke	JF	2007-Apr-19	0.34	2.21	3.30	-24.31	4.7E-3	3.5	11.1 15.1	~8
4P/Faye	JF	2006-Nov-15	1.67	6.03	7.55	-22.49	5.2E-2	2.0		10.0
6P/d'Arrest	JF	2008-Aug-14	1.35	5.63	6.53	-23.26	2.6E-2	2.3	6.7 7.2	6.4
8P/Tuttle	HT	2008-Jan-26	1.00	10.4	13.5	-23.61	3.8E-2	7.8		6.7
19P/Borrelly	JF	2008-Jul-22	1.36	5.86	6.86	-22.84	9.9E-2	3.3	25	8.2
22P/Kopff	JF	2009-May-15	1.58	5.35	6.46	-23.09	2.51E-1	2.0	12.3	8.4
26P/Grigg-Skjellerup	JF	2008-Mar-23	1.12	2.96	5.11	-23.93	3.0E-3	1.6		11.8
46P/Wirtanen	JF	2008-Feb-02	1.06	5.13	5.44	-23.36	4.0E-1	0.6	7.6	8.9
67P/Churyumov-Gerasimenko	JF	2009-Feb-28	1.29	5.72	6.56	-22.42	1.8E-2	2.4	12.3	11.6
85P/Boethin	JF	2008-Dec-16	1.11	8.91	11.2	-23.46	---	---		7.4
88P/Howell	JF	2009-Oct-12	1.37	4.87	5.50	-22.77	3.04E-2	1.9		10.5
96P/Machholz 1 daytime only	HT	2007-Feb-24	.124	5.90	5.23	---	2.0E-2	3.2	6.38	2 (aerith) 14 (JPL)

Comets are up for more than 2 hours at less than 2 Air Masses (except 96P daytime), and T-mag are ≤12; most have known radii R_{nuc} and P_{rot}.



Future Observational Characterization of JF Comets and their Rimes
Mantle characteristics from Observations of an ensemble of JF comets:
• small active area fractions
• jets
• active areas persistent over > months
• active areas recurring from apparition to apparition
• dust-to-gas ratios [Afρ/CN, Afρ/OH] are smaller for comets with smaller perihelion distances q_{AU}
Active area fractions smaller for comets with smaller q_{AU} [Q_{OH}, R_{nuc}]
0.1–100 μm Grains
Comets with smaller q_{AU} have smaller Afρ due to lack of small grain scatterers [Afρ, a_p >10 μm]
=
Comets with larger q_{AU} have small grain scatters [Afρ, a_p <10 μm]
Coma Gases
Comets with smaller q_{AU} produce more CN; implying q_{AU}-dependent CN distributed source from grains [CN radial profile]
Color Maps
grain size n,k
Polarization
aggregate size composition porosity
IR SEDs
peak grain radius (a_p), mineralogy porosity
coma-trail shapes
β, v_{exp} temporal activity jet locations
light curves
temporal activity
Q_{gas}
coma composition
β
Mineralogy of small grains released from SP comet Active Areas
? Fragmentation of small grains
? CN-producing grains do not produce Afρ [Afρ, CN profiles]
? CN, C_2, C_3 related; NH not related
Implications
Interpretation of Colors of nuclei: small grains (a_p < 0.5 μm) may yield %/1000Å≈0
Resolve degeneracy in interpretation of Spitzer IRS+MIPS of JFCs at large r_H: small grains or large (>mm) chunks?
Range of SP comet compositions: probe solar nebula conditions; bimodal or continuous range of mineralogies probes nucleus layered pile model & mixing scales
Grain aggregation & composition: Submicron CHON grains; Organic glue binds silicate subgrains; Core-mantle (birdsnest) aggregates vs disequilibrated mineral aggregates