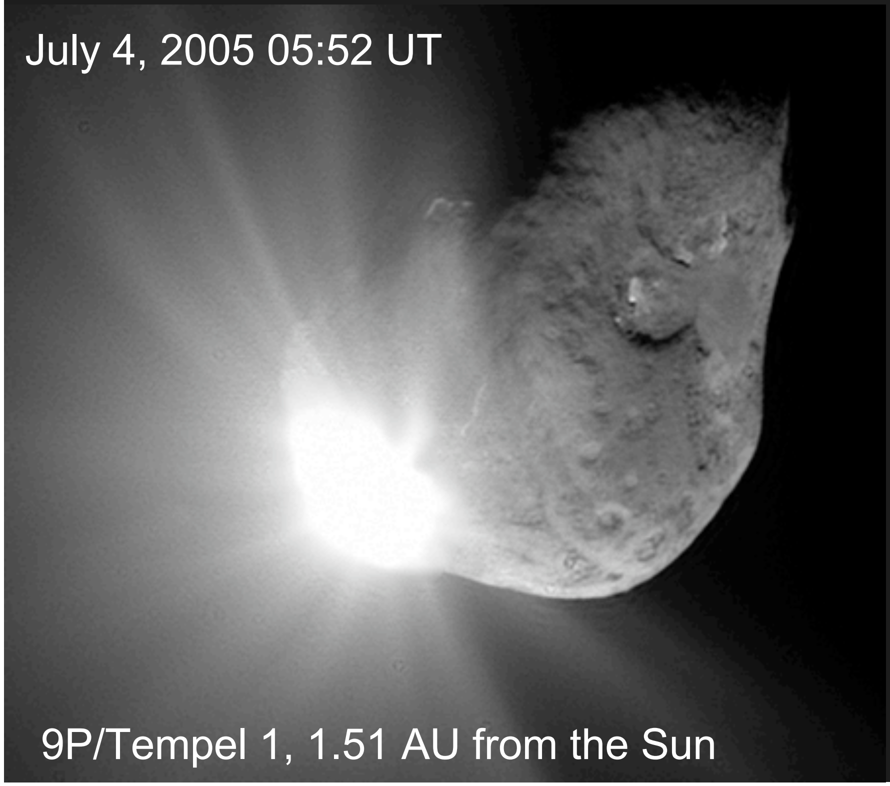
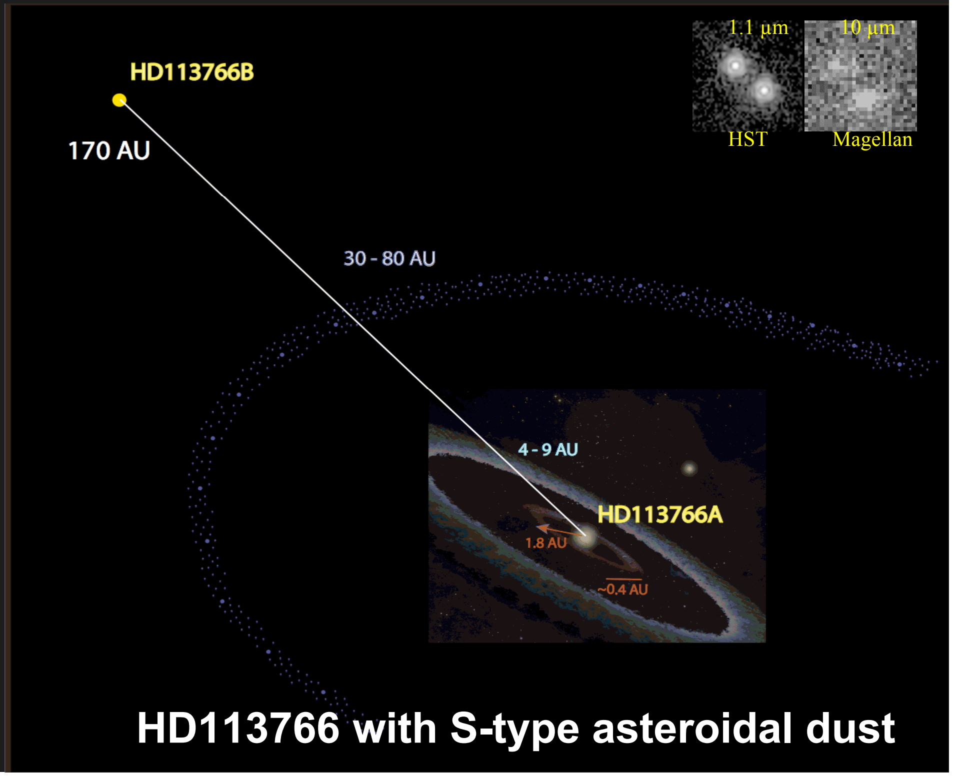
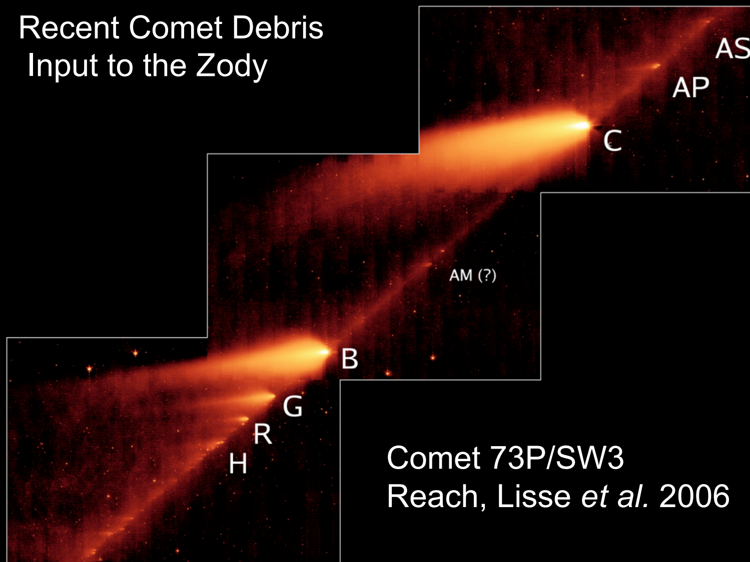
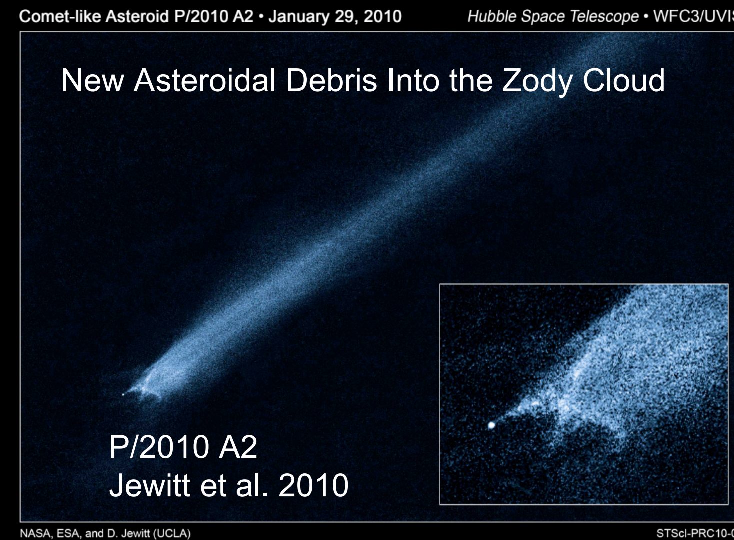
Estimates of the Composition & Kind of Zody Dust from Remote Sensing Spectral Observations

Dr. Carey Lisse
Johns Hopkins University Applied Physics Laboratory
University of California at Irvine, 26-Mar-2010





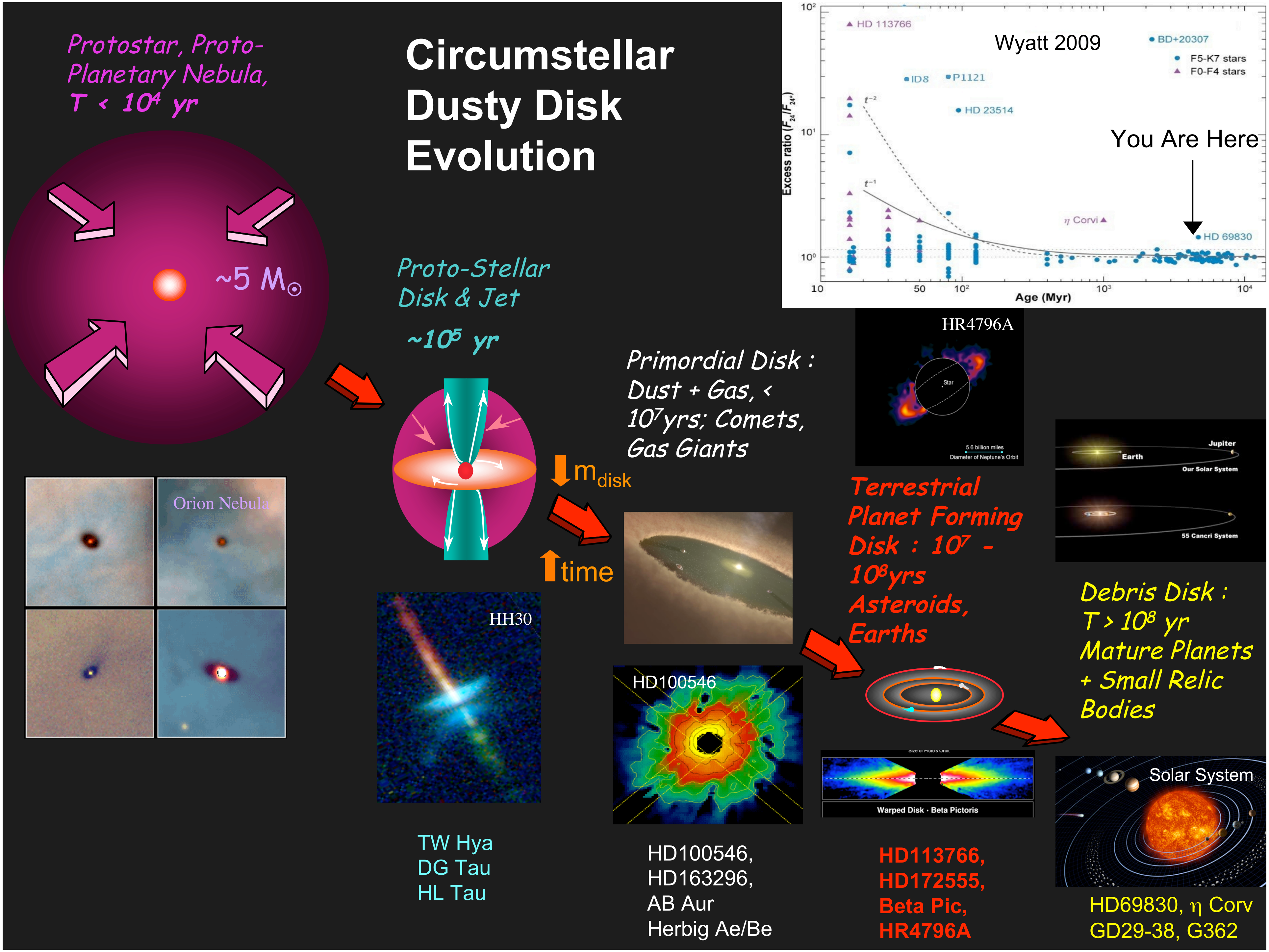




Debris Disks: Ours, Theirs

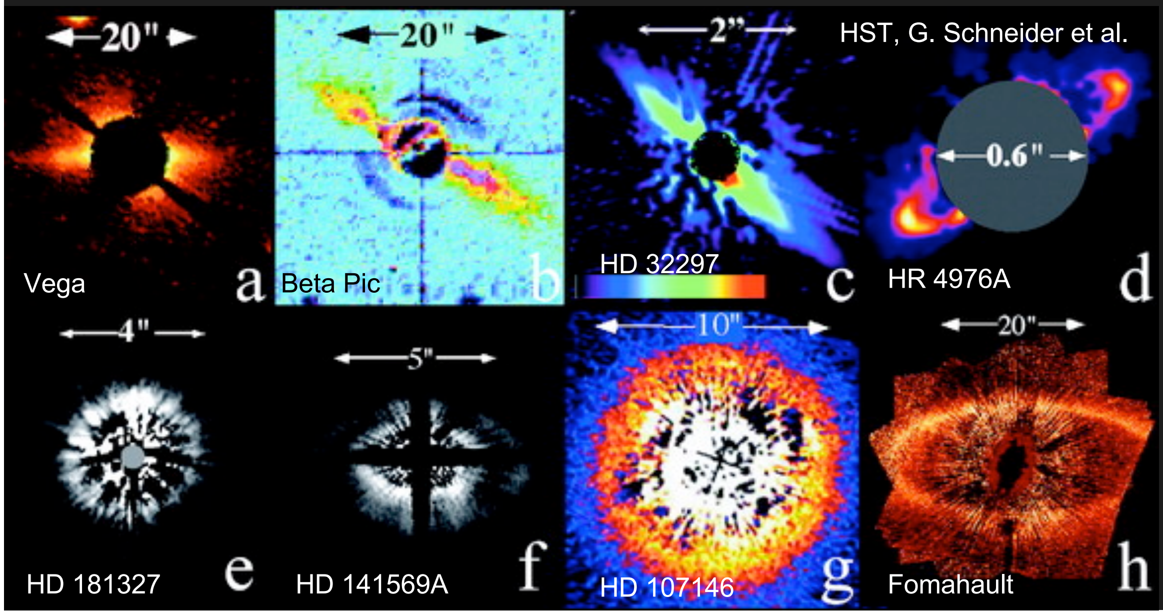
Yesterday heard from David, Bill, Mikhail & Stan about Zody Cloud structure & inputs

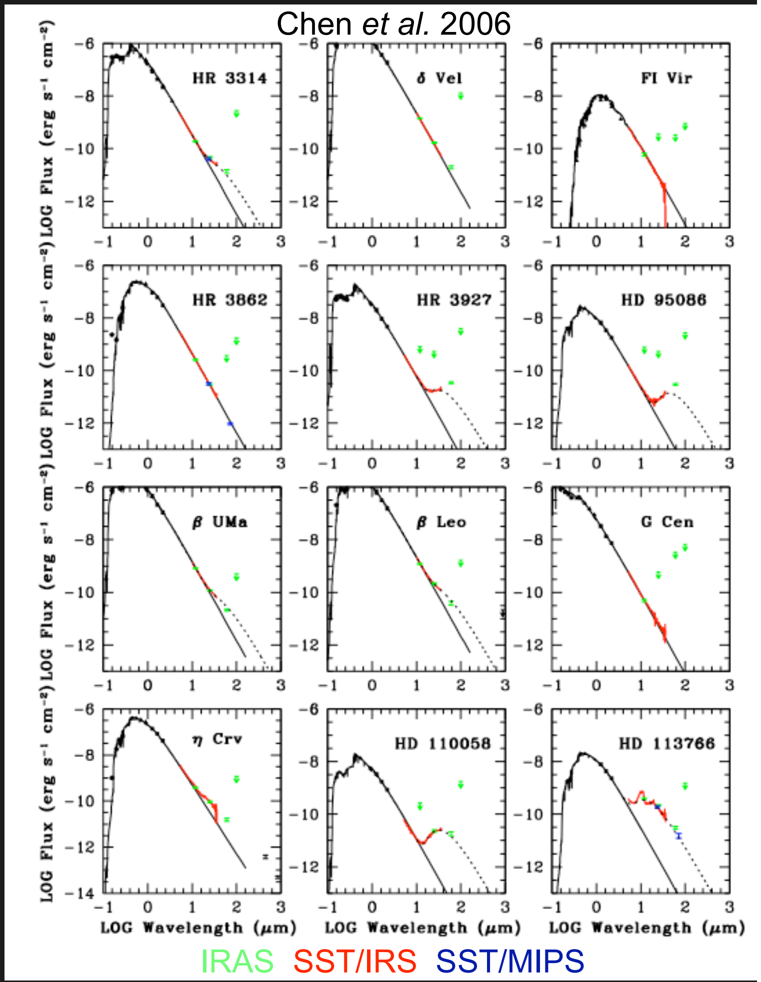
- We know zody from comets (comae, tails, trails, meteor streams)
- We know zody from asteroids (zody bands, trails, P/2010 A2)
- Kuiper Belt input suspected from Pioneer, NH # densities vs r_h


Protostar, Proto-Planetary Nebula, T < 10^4 yr
~5 $M_\odot$
Orion Nebula
Circumstellar Dusty Disk Evolution
Wyatt 2009
HD 113766
BD+20307
F5-K7 stars
F0-F4 stars
ID8
P1121
HD 23514
t^{-2}
t^{-1}
You Are Here
η Corvi
HD 69830
Excess ratio (F_{24}/F_{24*})
Age (Myr)
Proto-Stellar Disk & Jet
~10^5 yr
m_{disk}
time
HH30
TW Hya
DG Tau
HL Tau
Primordial Disk : Dust + Gas, < 10^7yrs; Comets, Gas Giants
HD100546
HD100546,
HD163296,
AB Aur
Herbig Ae/Be
HR4796A
Star
5.6 billion miles
Diameter of Neptune's Orbit
Terrestrial Planet Forming Disk : 10^7 - 10^8yrs Asteroids, Earths
Warped Disk · Beta Pictoris
HD113766,
HD172555,
Beta Pic,
HR4796A
Earth
Jupiter
Our Solar System
55 Cancri System
Debris Disk : T > 10^8 yr Mature Planets + Small Relic Bodies
Solar System
HD69830, η Corv
GD29-38, G362

Disks Happen! And So Do Belts/Toroids, and Kuiper Belts

- More than 100 resolved disk systems are now known
- Primordial disks are common (~70% of all PMS stars)
- Kuiper Belts are common (> 20% of stellar systems; Bryden *et al.* 2006)
- Warm Dust detections in exo-disks is rare (~2% of MS stars; Beichman *et al.* 2007)

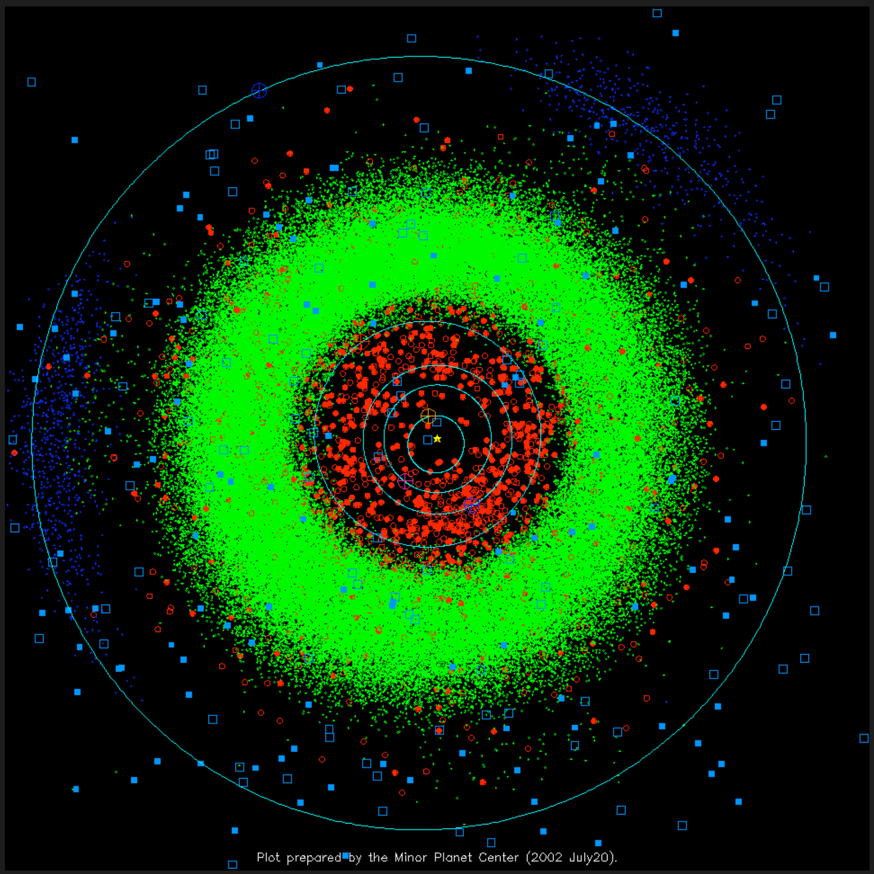




- 'Fab 4' : Epsi Eri, Vega, Beta Pic, Fomahault have complex spectra

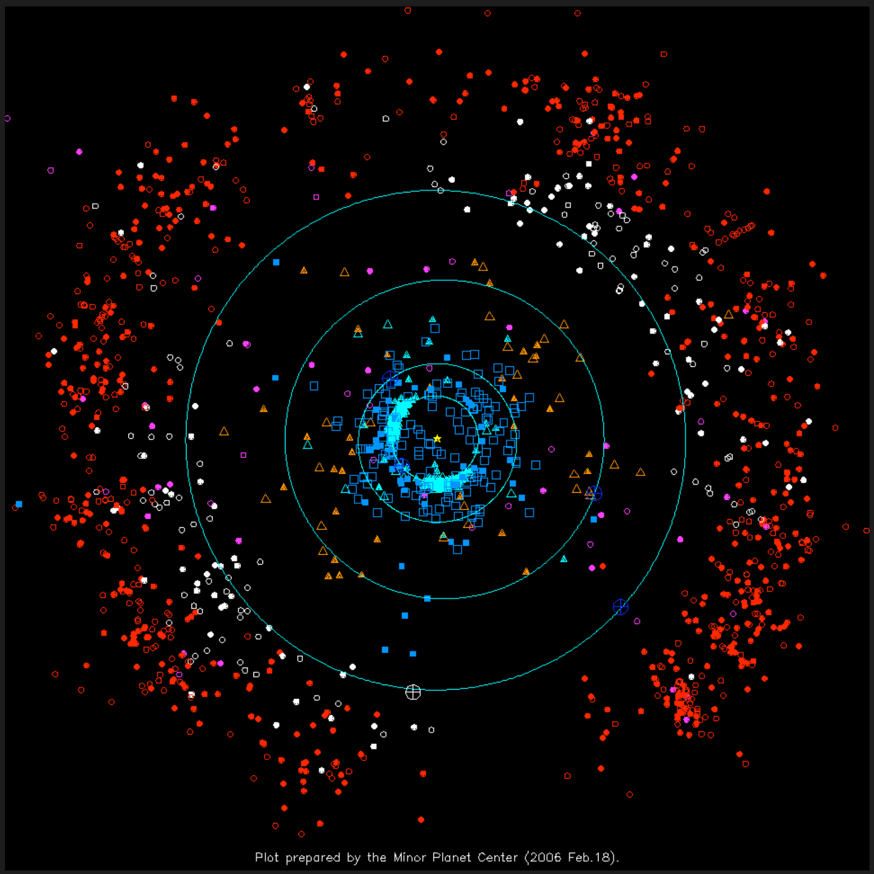
The Local Evidence : While mostly cleared out, the Solar System does contain 2 sparse (< 1% of original density) Debris Disks & an Oort Cloud (not shown)

Inner System
(green = asteroid belt)



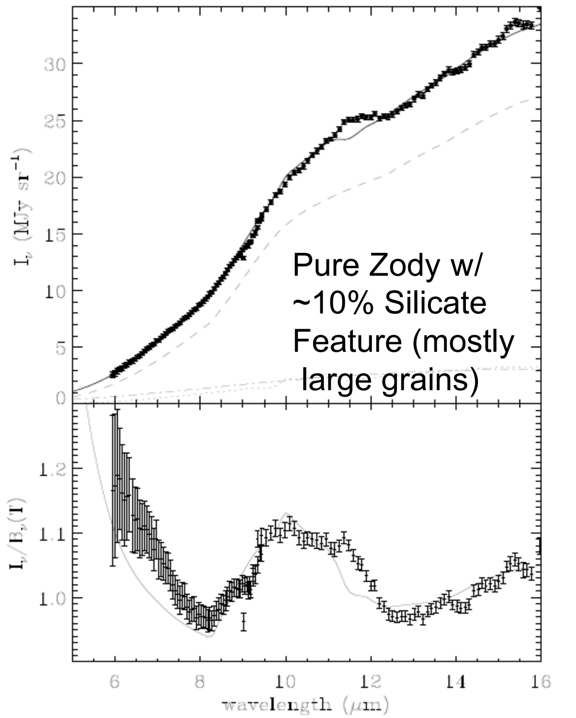
|------------ 10 AU ------------|

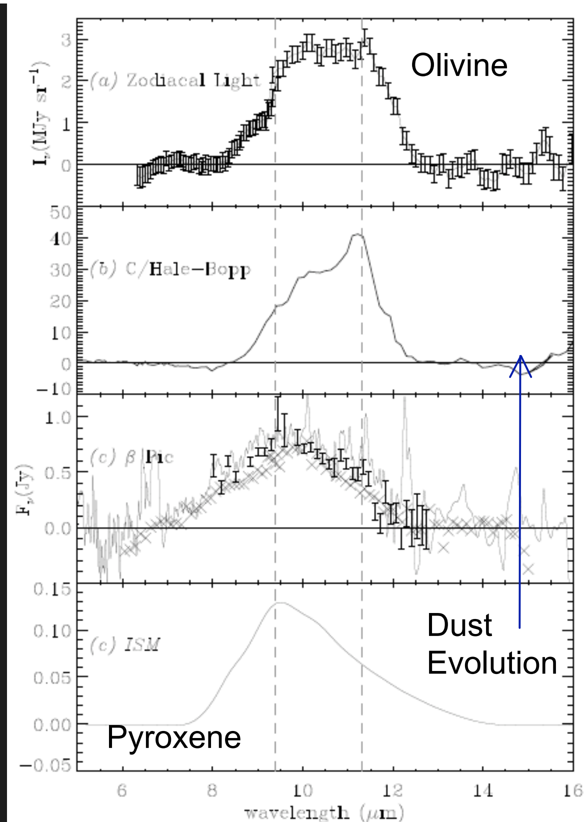
Outer System
(red = Kuiper Belt)



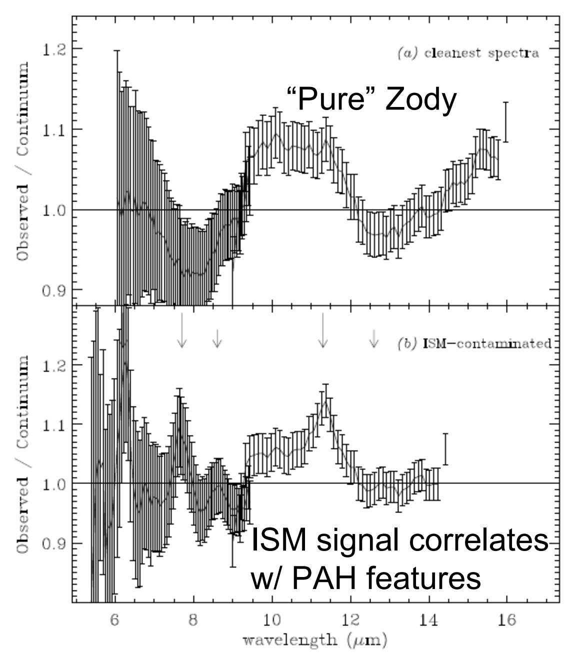
|-------------100 AU -------------|

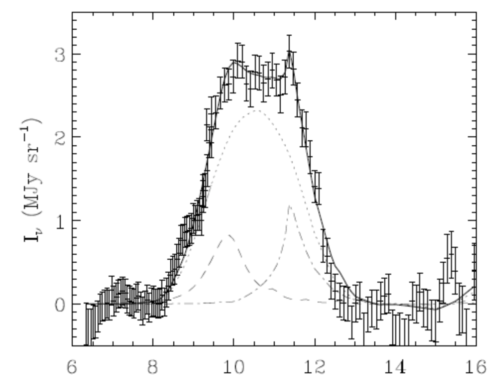
Zody Light Spectra from ISO – Small But Finite Silicate Emission Feature. (Reach *et al.* 2003)





But: Need to update spectral analysis for Deep Impact, STARDUST, dynamical, & Spitzer lessons learned re: cometary & asteroidal dust.





Best Decomposition = ~20% Asteroid +80% Comet

Fig. 13.— Comparison of a mixture of silicates with all possible ellipsoidal shapes to the observed, continuum-subtracted, spectrum of the zodiacal light. The solid line is the mixture fit, the dotted line is the amorphous olivine contribution, the dashed line is the montmorillonite contribution, and the dash-dotted line is the crystalline olivine contribution.

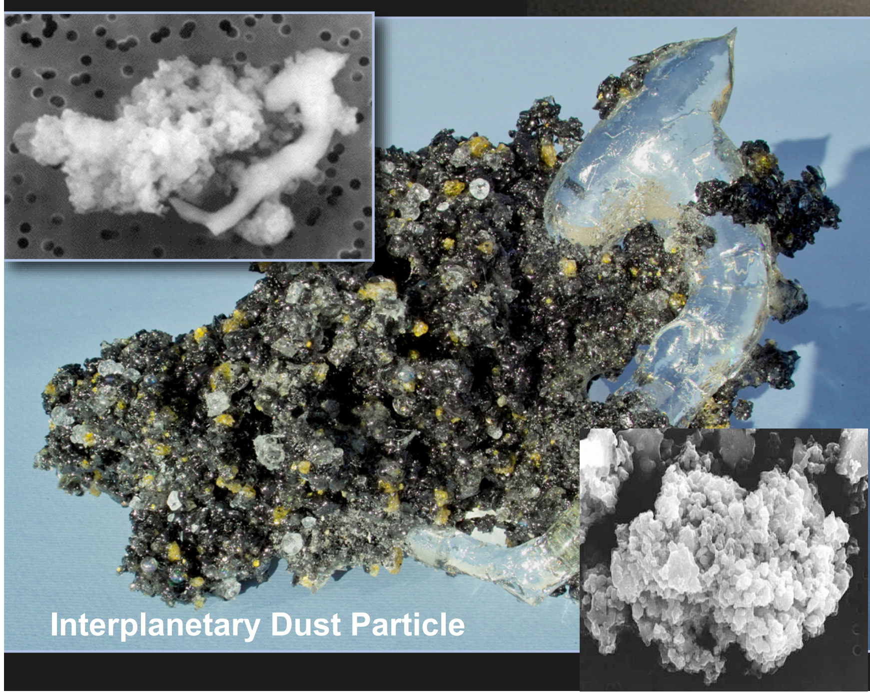
See also:
Messenger & Keller - (IPD like Hale-Bopp)

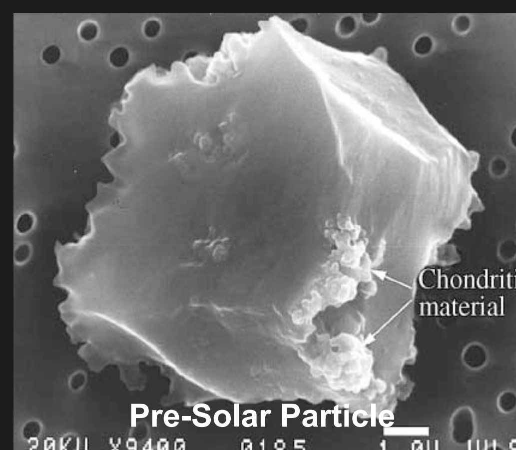
New CIBER Results- Zody Refl. Like S-Type Asteroids

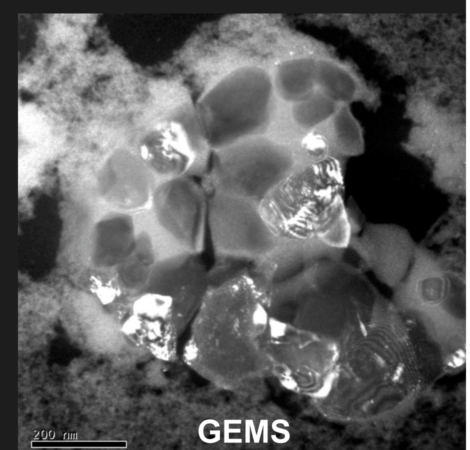
Nesvorny IRAS Fitting - >90% of IPD input is from JFCs

Composition & Structure:

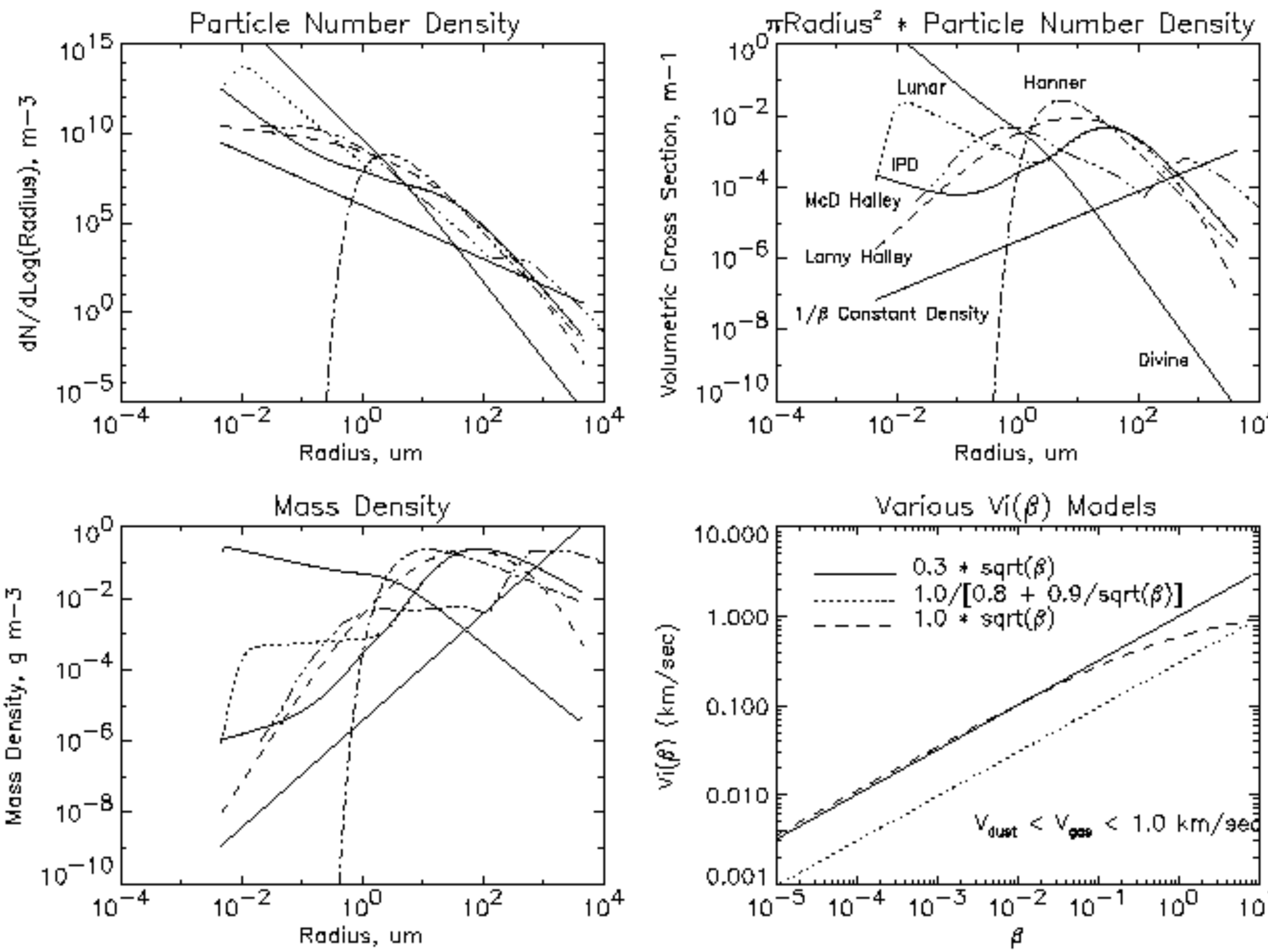
~10 major atomic constituents [H,C,N,O,Si,Mg, Fe,S, Al, Ca, Na…] contained in ~7 Refractory Species + Volatile Ices







Relevant Dust Size Distributions

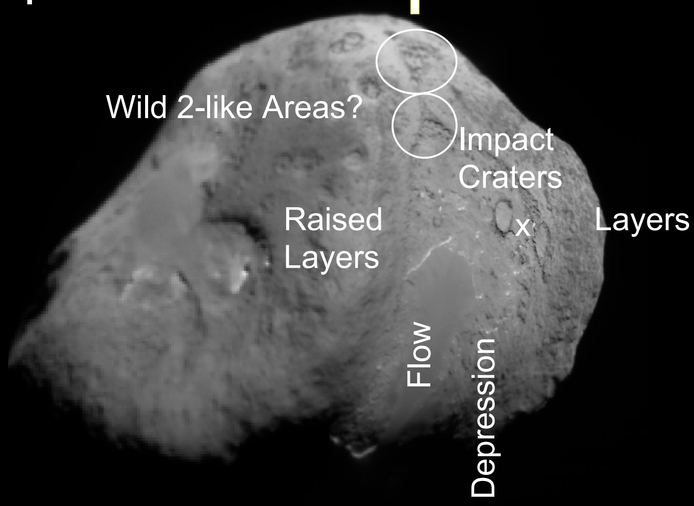


Lisse *et al.* 1998

Those Pesky Comets

(aka Cosmic Dust Bunnies,
Vermin of the Sky II, etc.)

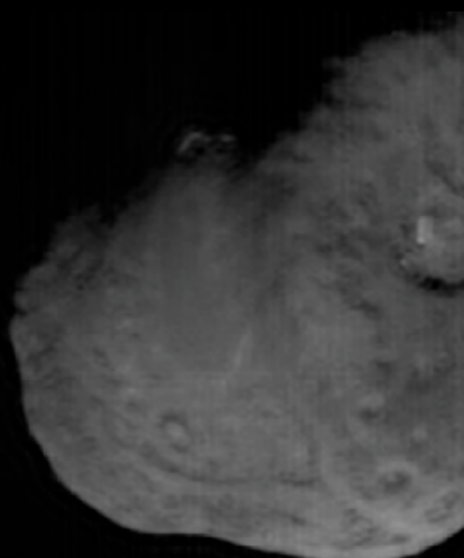
Deep Impact Experiment



Impactor (ITS)

Note one big jitter early due to thruster course correction. Big jitters in last 30 seconds are due to dust hits.

Flyby (HRI)



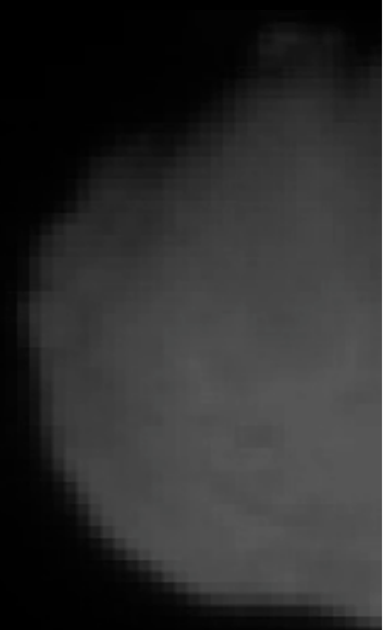
3-part Lightcurve observed:

Contact flash (19GJ @ 10.2 km/sec +

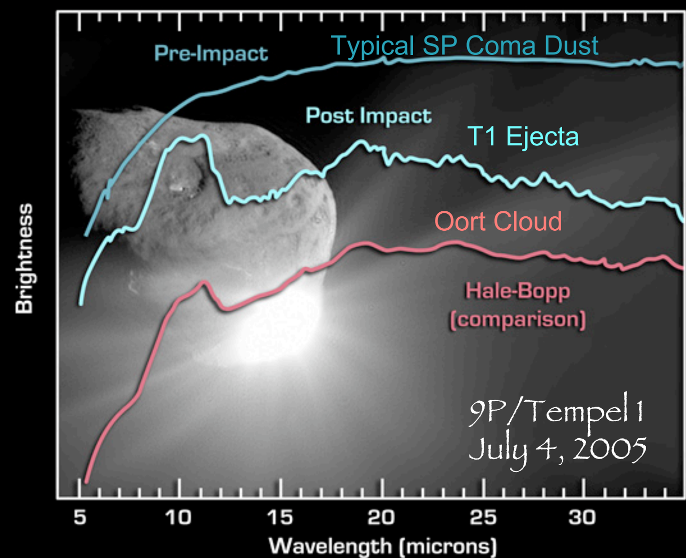
5 km/sec Gas Plume +

1m/sec Dust Ejecta.

Flyby (MRI)



Deep Impact and the STARDUST Comet Sample Return have Created a New Era of IR Dust Compositional Studies. Comets are now known to be Highly Processed Mixes of ISM material.



Comet dust only reveals its compositional signatures on remote IR observations when finely divided, as in the Deep Impact experiment or in the violent outflow from hyperactive comets like C/Hale-Bopp 1995 O1

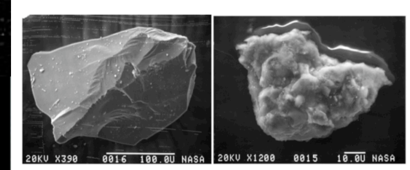
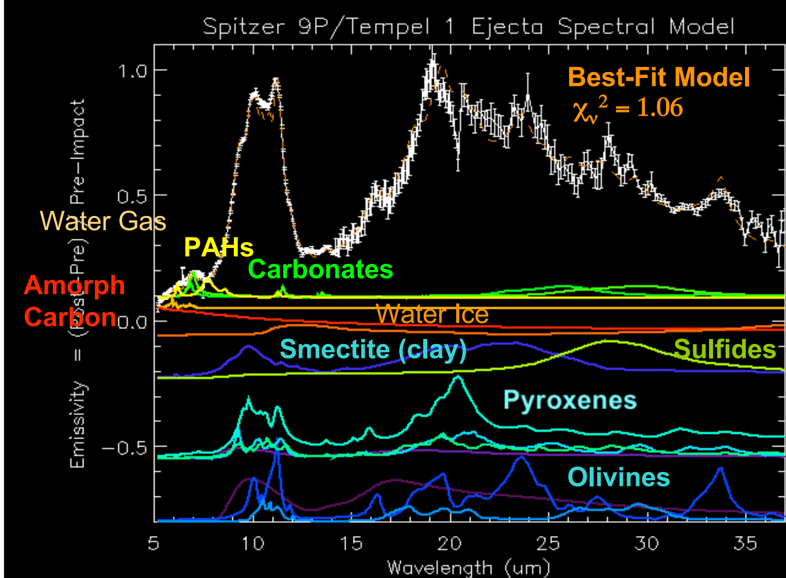


Figure 8. SEM images of a typical olivine grain before (left) and after (right) launching into aerogel in light gas gun experiments at JSC (after Barrett et al., 1993).

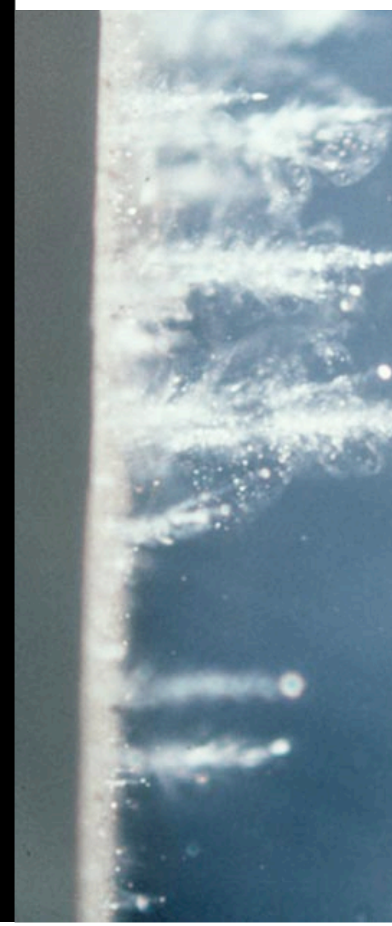
Compound Dust Particle

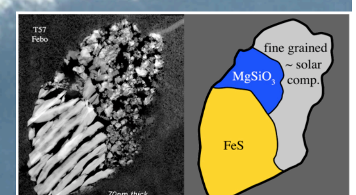


Spitzer IRS 1+45 Min
344 Spectral Points
SNR 5 - 30 (2σ errors)
➢16 Sharp Features
95% C.L. = 1.13

Laboratory Powder Emission Spectra

Lisse *et al.* 2006

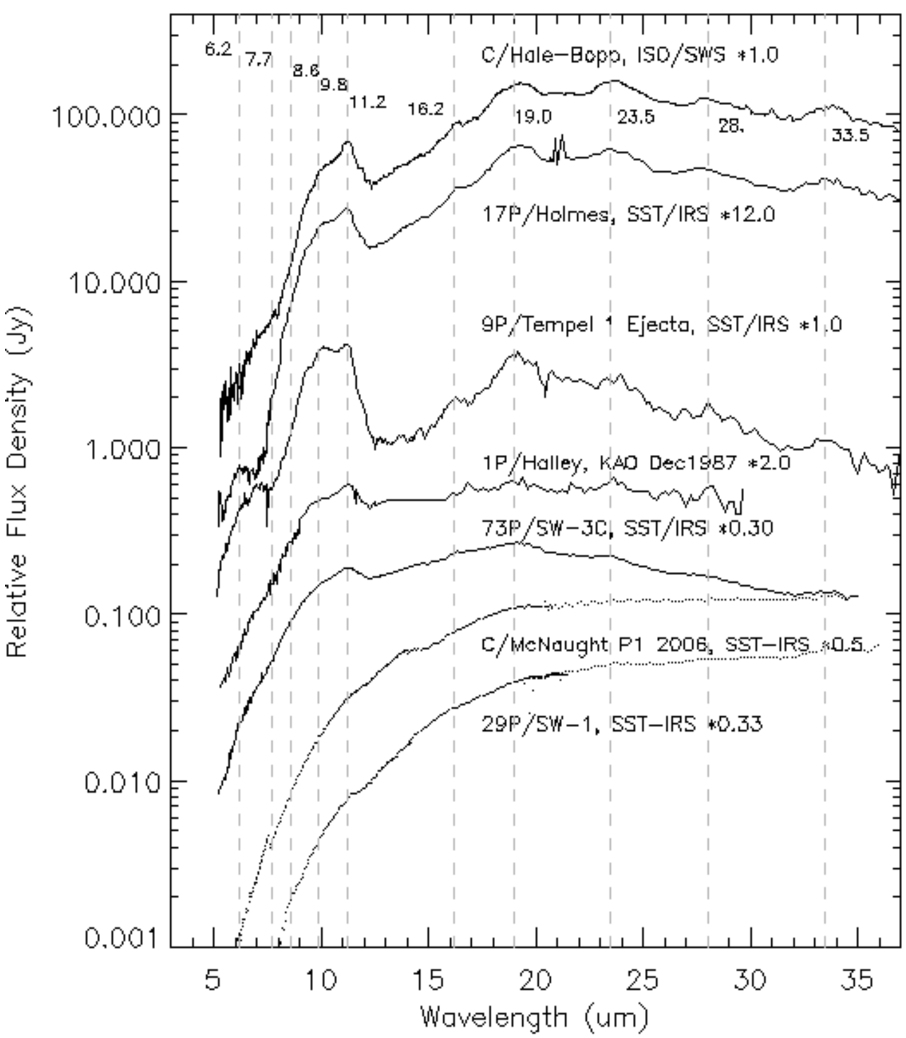


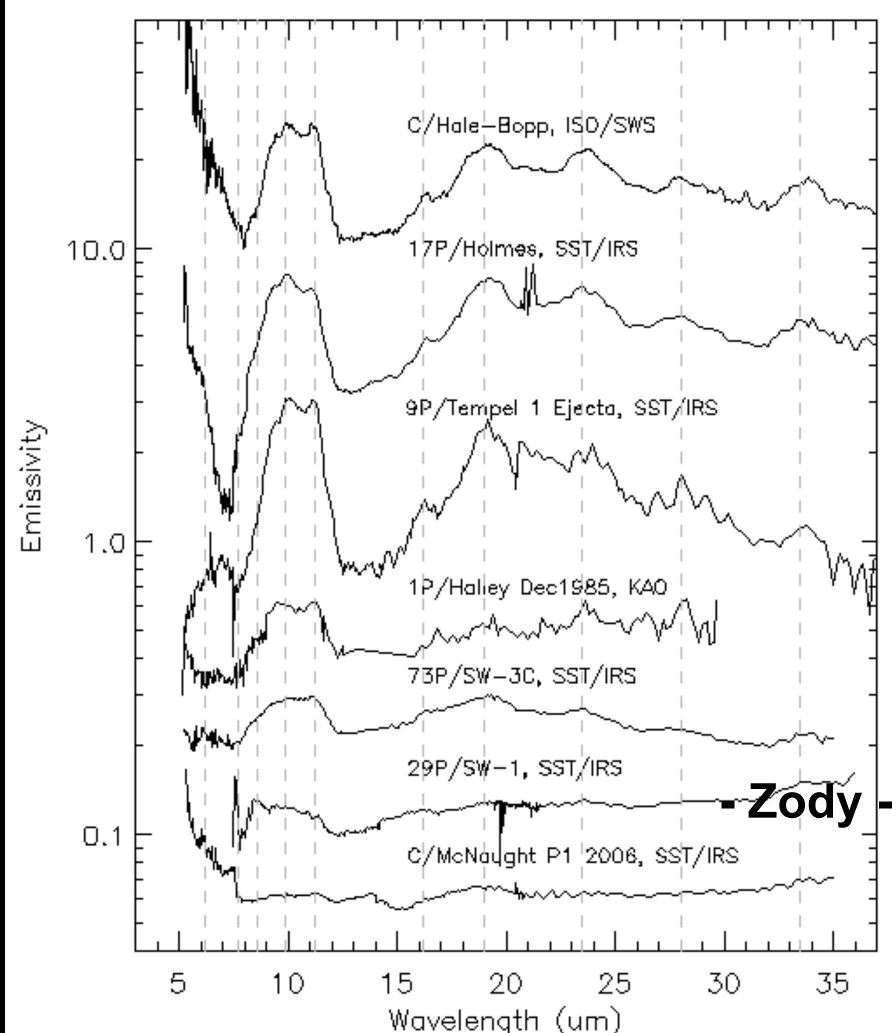


Hypervelocity Dust Particle Capture into Aerogel : Ferro-Magnesian Silicates, Metal Sulfides, Refractory Carbon, Carbonates

Recent Bright Comet Spectra, Emissivities

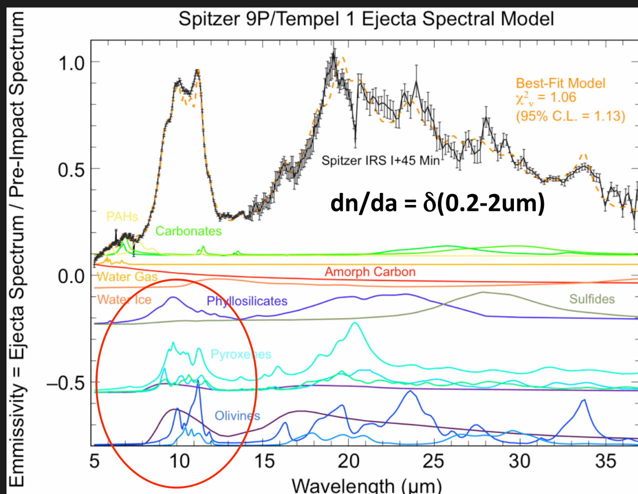
Variability Due to PSD Differences



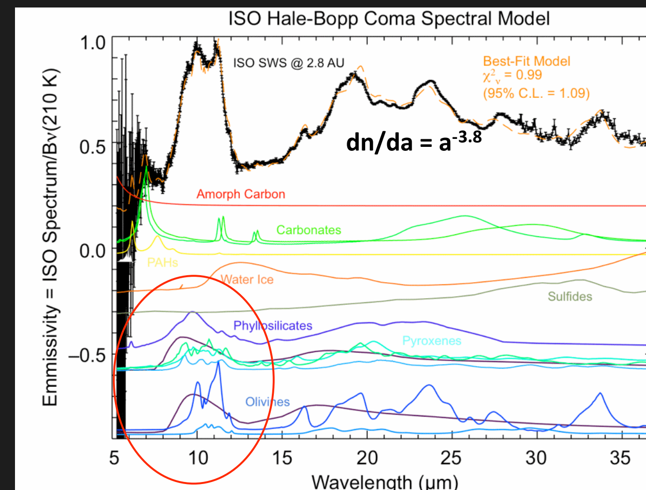


4 & 1/2 Comets in the Mid-IR :

Mixes of Silicates, Water, PAHs/Amorph Carbon, Metal Sulfides



Tempel 1
SP
$R_h = 1.51$ AU
Q ~ 10^{28}
D/G > 1.3

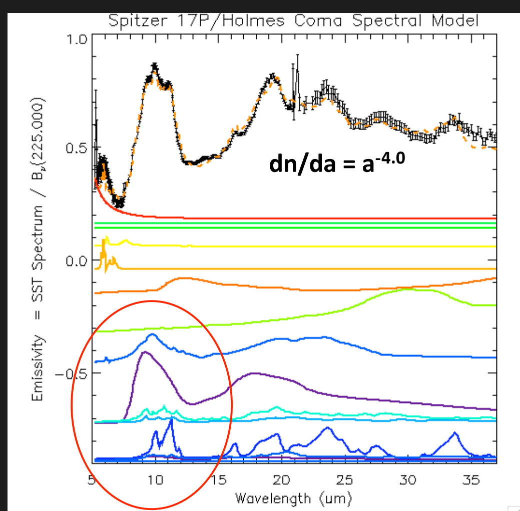


Hale-Bopp
LP
$R_h = 2.8$ AU
Q ~ 10^{30}
D/G ~ 5

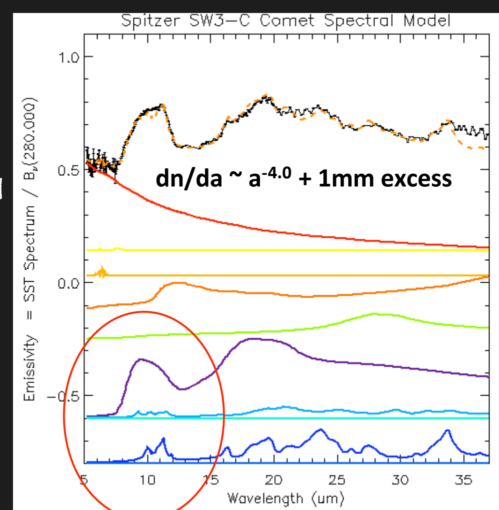
> 80% crystalline, Fe/Mg impact equilibration

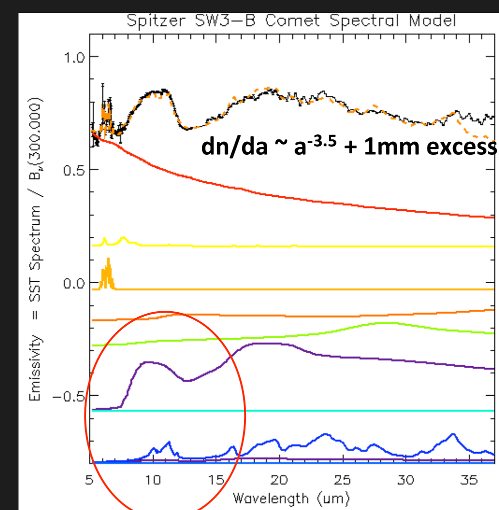
> 70% μ-crystalline, FeS + Mg silicates

Holmes
SP
$R_h = 2.4$ AU
Q ~ 10^{30}
D/G ~ 3



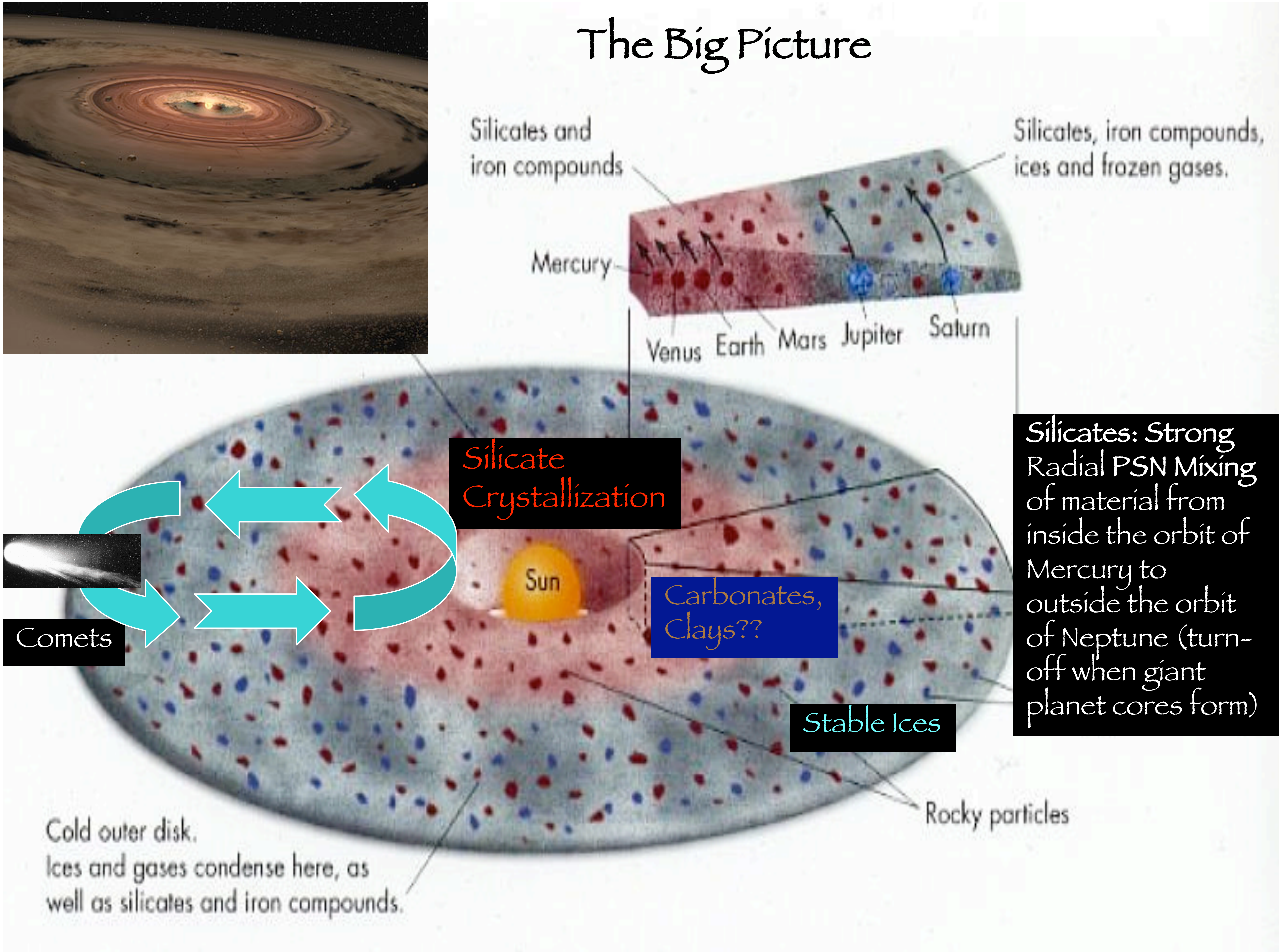
SW3-C,B
SP
R_h ~ 1.4 AU
Q ~ 10^{28}
D/G ~ 2





Primitive : 20 - 30% crystalline, FeS + Amorph Sil + Mg-Olivine

The Big Picture

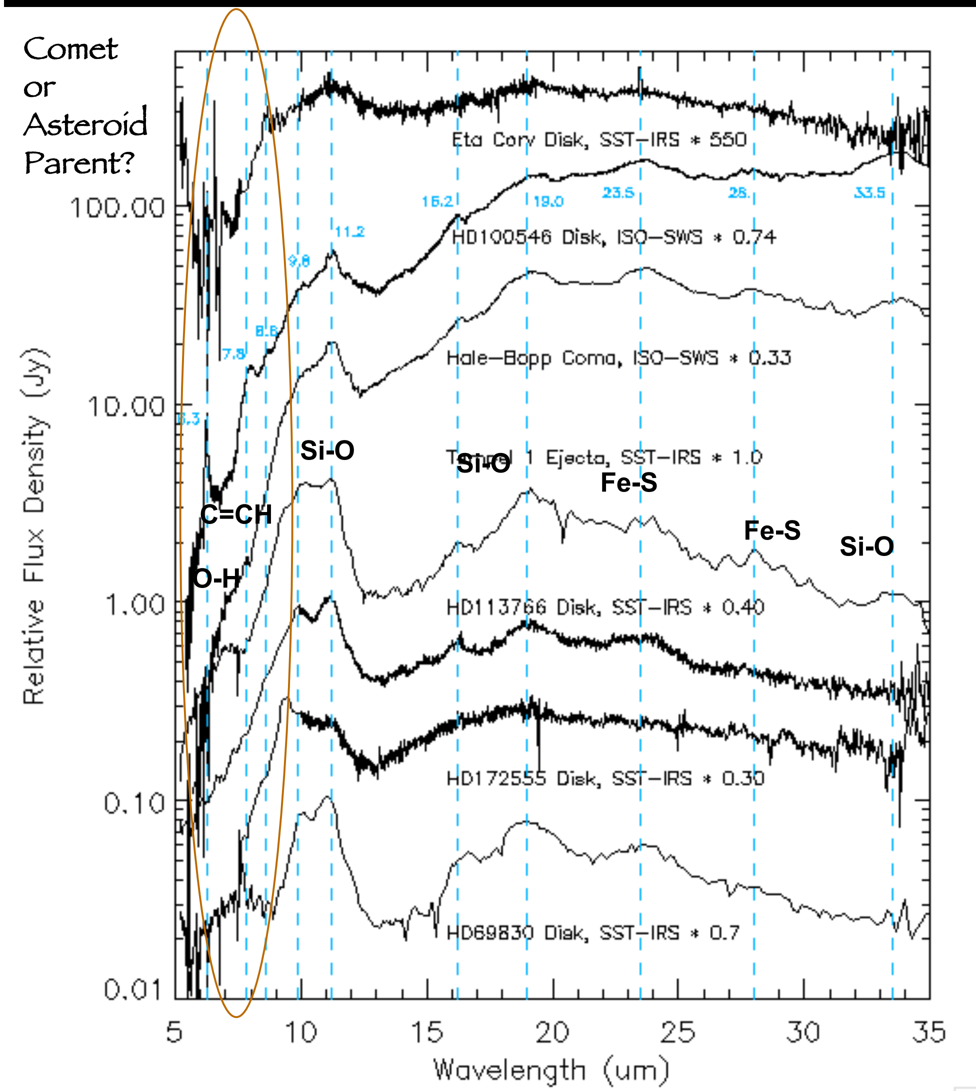


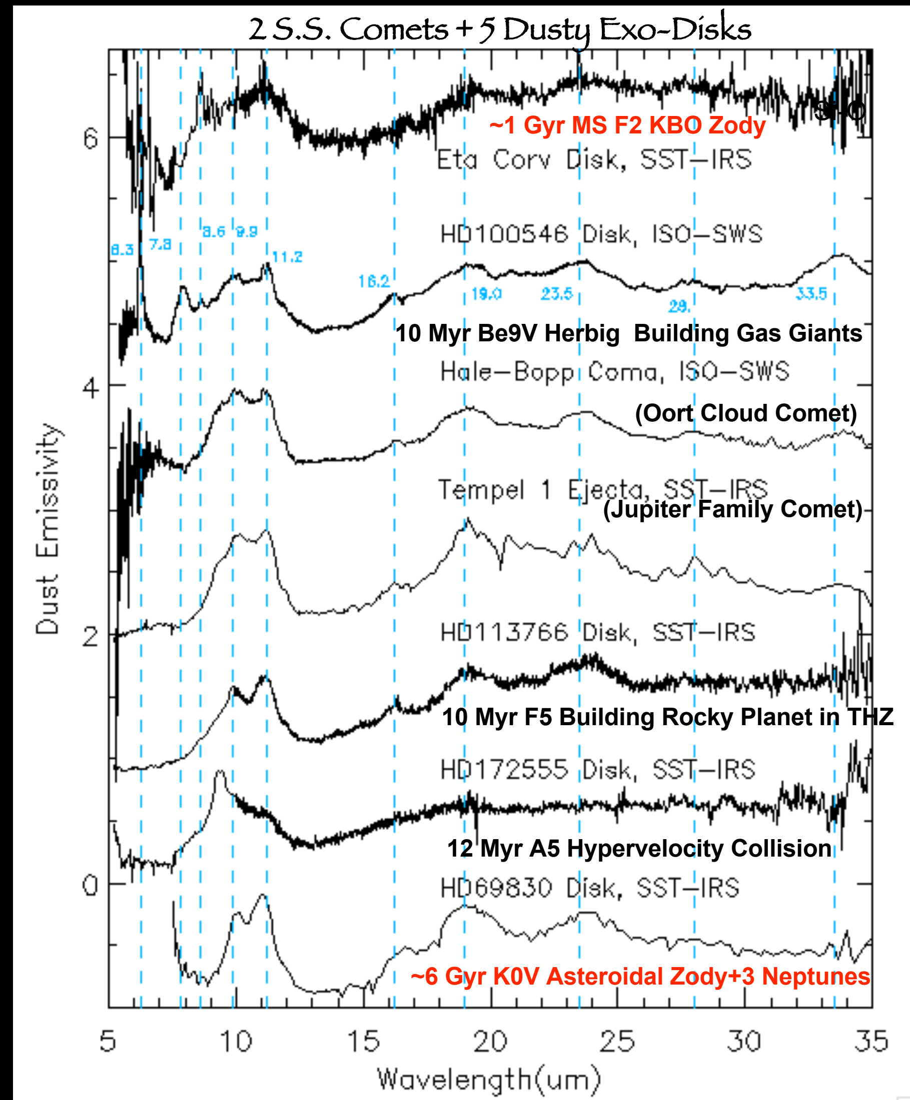
Best Zody Exo-System Analogues

Composition of IZC: Comet Dust + Main Belt Asteroid Dust (S-type, C-type, etc.) + some KBO Dust

Composition of OZC: Comet Dust + KBO Dust (w/ Ices?)

Selected Exo-System & Comet Emissivity Spectra : Systems studied to date have similar spectral features due to the near-ubiquitous presence of silicates, metal sulfides, and amorphous carbon, [+PAHs, water gas/ice, and carbonates for cometary/primordial systems].

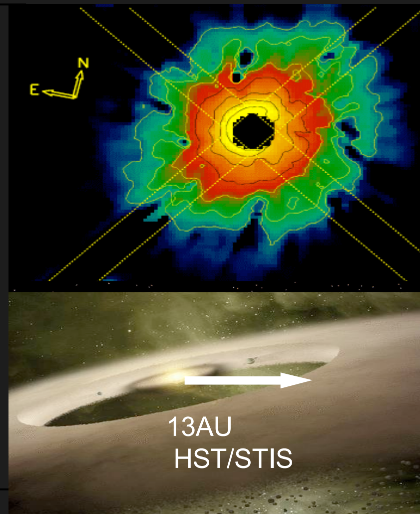




Gas Giant & Rocky Planet Building Objects

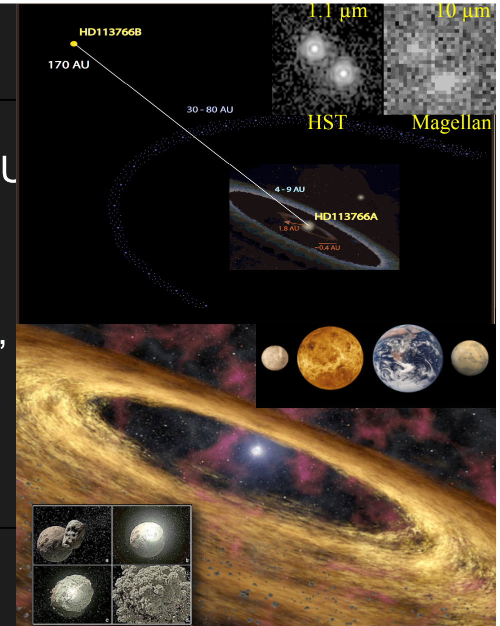
Herbigs HD100546 & 163296: Comet-like system spectra. Especially rich in Mg-rich olivine and amorphous ISM pyroxene, water ice. ~10 My old, >> M_{earth} of material at ~13/7 AU at an inner disk cavity edge (c.f. Grady *et al.* 2005).

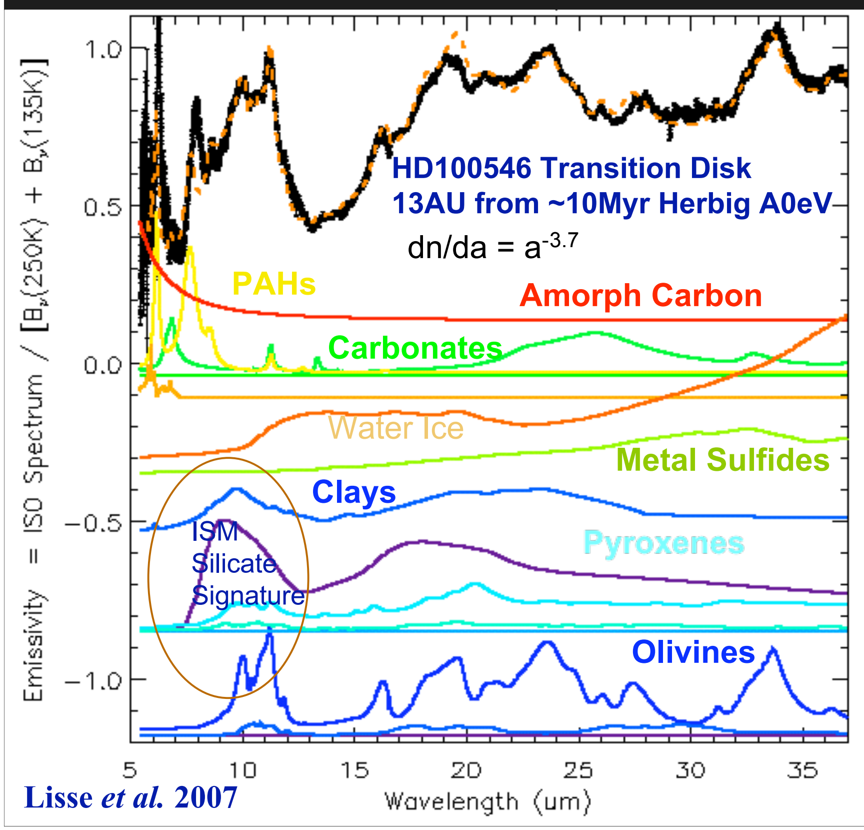
=> Building Giant Planets w/ KBO planetisimals?



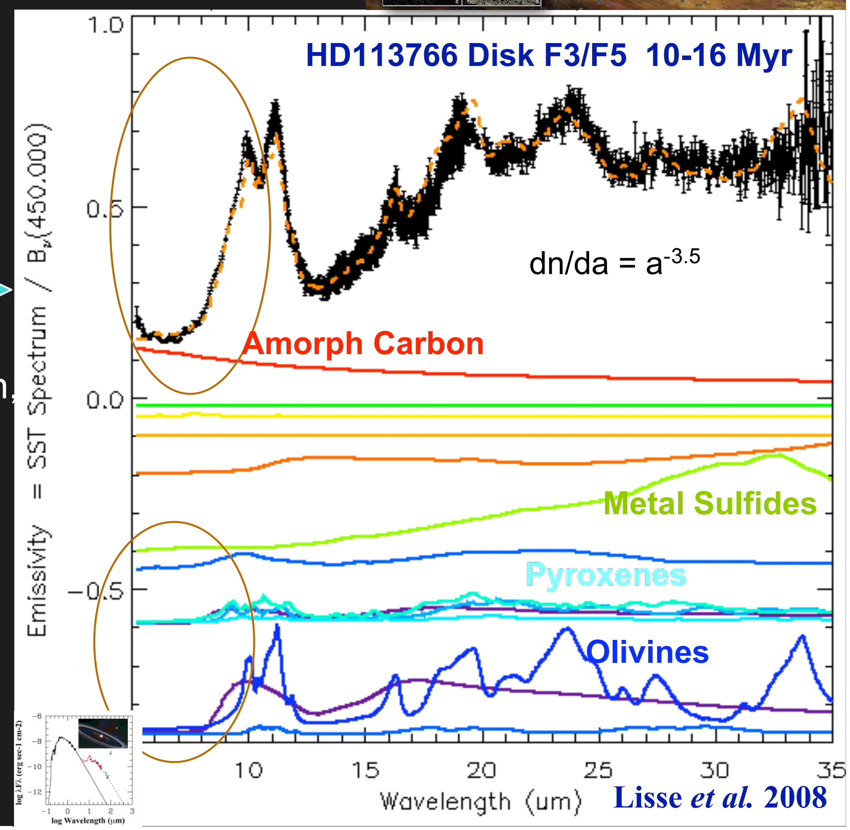
HD113766 : 10-16 My old.

- 0.5M_{Mars} of Dust @ ~1.9 AU from HD113766A, has Mg-rich olivine, Fe-rich sulfides, amorph carbon, and xtal pyroxene. Solar abundance, S-type asteroid composition in the heart of the terrestrial planet zone. => **Ongoing Rocky Planet Formation.**



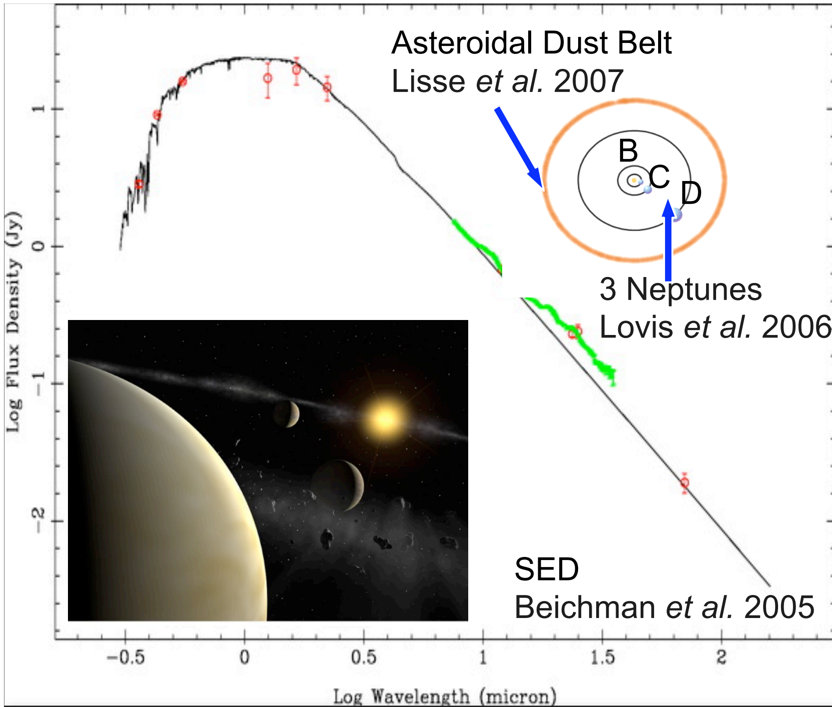


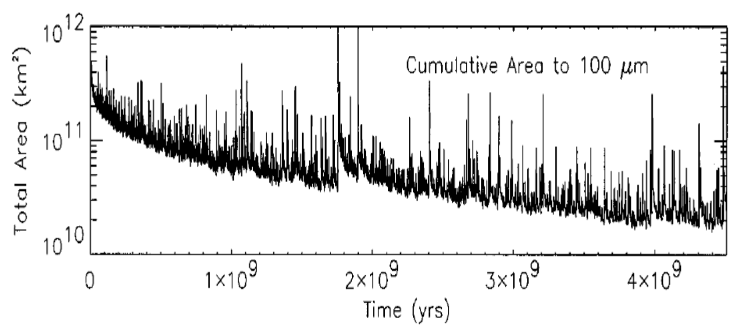
Disk Evaporation, Gas Depletion?



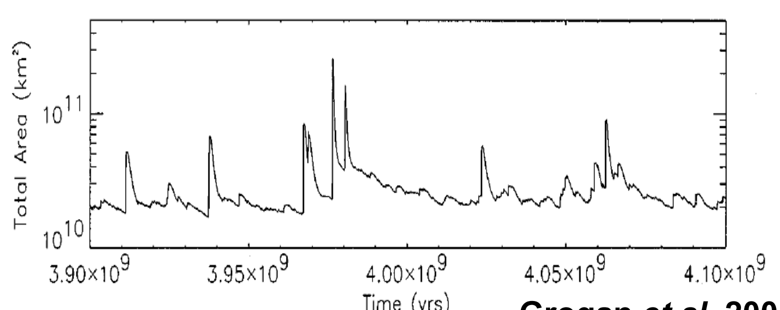
Dense, Mature Debris Disk of HD69830

- K0V, T = 5400 K, 2 - 10 Gyr old, 12 pc distant
- Small, icy, ephemeral dust replenished by ongoing fragmentation of an ~30 km radius C asteroid disrupted @ 1 AU. (Like Karins/Veritas MBAs in the solar system 5-8 Mya?)
- 3 Neptune Sized Planets @ 0.08, 0.16, 0.63 AU

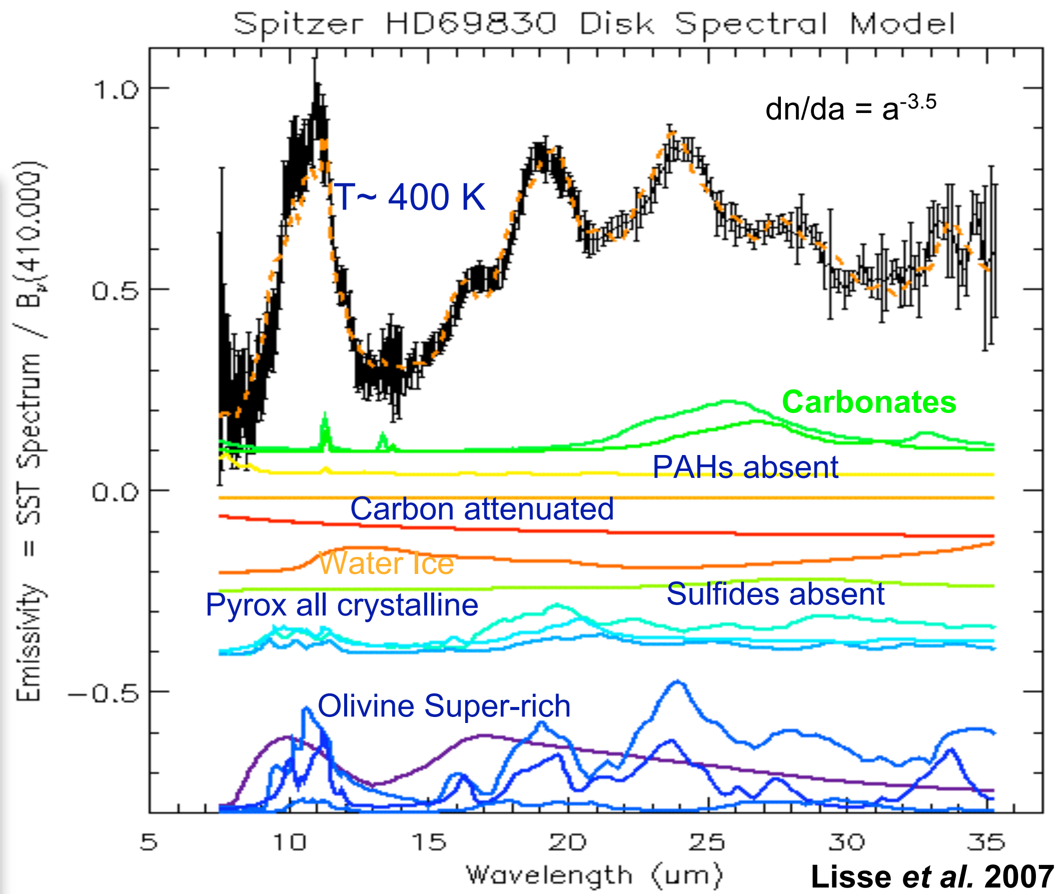




Dust Evolution in the Solar System Zody Cloud



Grogan *et al.* 2001



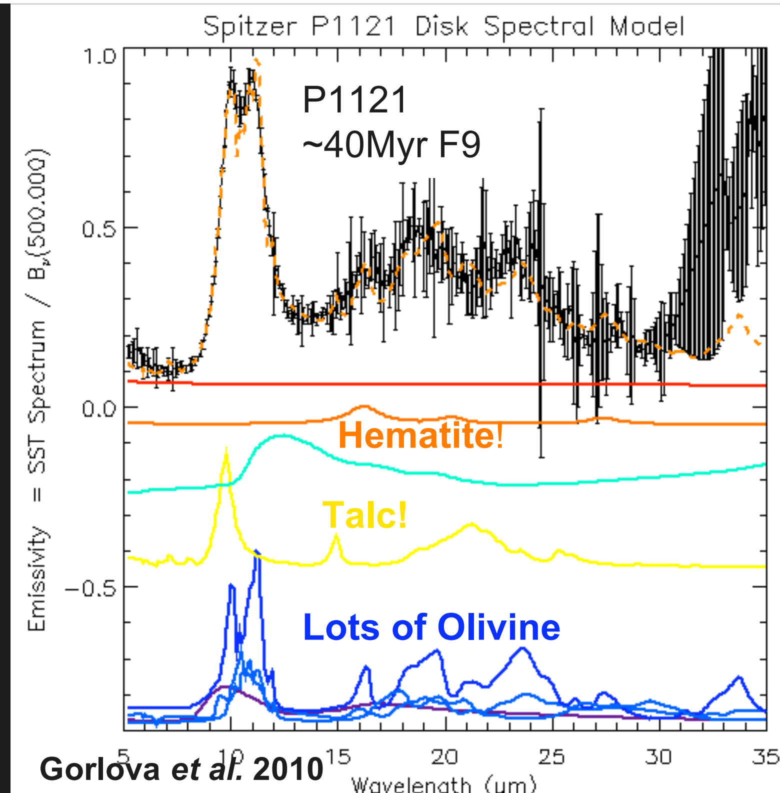
Lisse *et al.* 2007

ID8

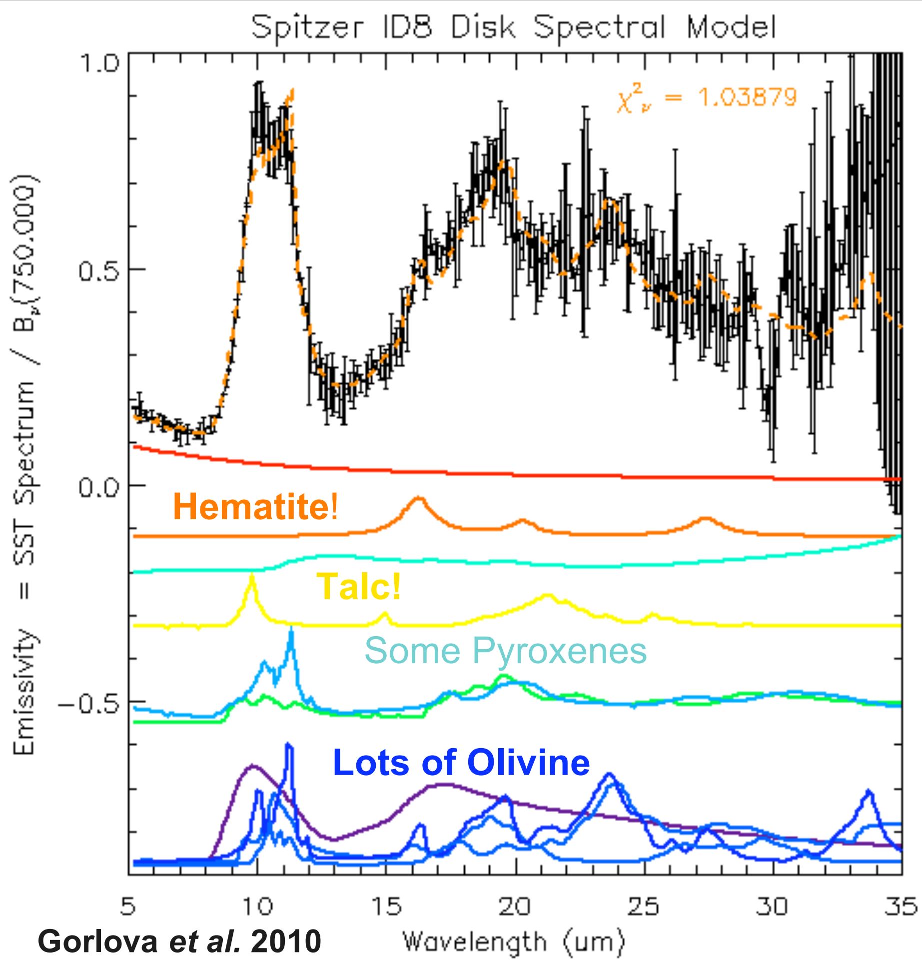
~80 Myr old NGC 2547 member, 450 pc distant.

Hot 750K dust @ 0.23 AU from an $0.8L_{¤}$ G7.

3×10^{19} kg, >120 km radius **C-type asteroid (2nd most abundant MBA)** parent body.



Gorlova *et al.* 2010



Gorlova *et al.* 2010

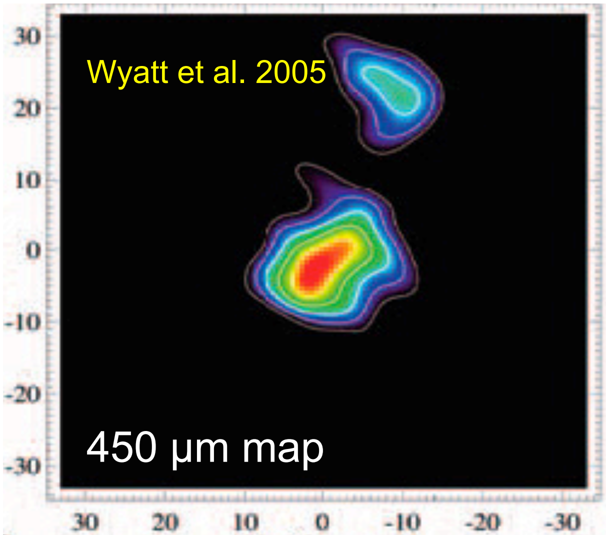
Spectrum dominated by emission from silicates, mainly Mg-rich olivines (80%) and crystalline pyroxenes (20%). Amorphous pyroxene is conspicuously lacking. The ratio of total olivine to pyroxene abundance is very high, ~ 4:1. Talc and hematite detection unique to these systems. Both results indicatefor high-T aqueous processing of the rock forming species.

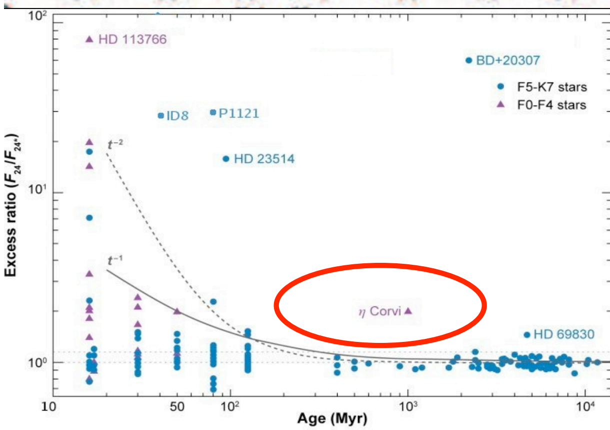
Iron and Sulfur/Sulfides. Some of the major sources of iron found in the cometary systems, the carbonate siderite ($FeCO_3$) and the Fe sulfides (pyrrohtite, ningerite, and pentlandite), are totally lacking in the ID8 debris disk. The major source of Iron in the dust is in the highly oxidized (and most likely aqueously altered) hematite (Fe_2O_3), consistent w/ the presence of the aqueous alterationphyllosilicate talc.

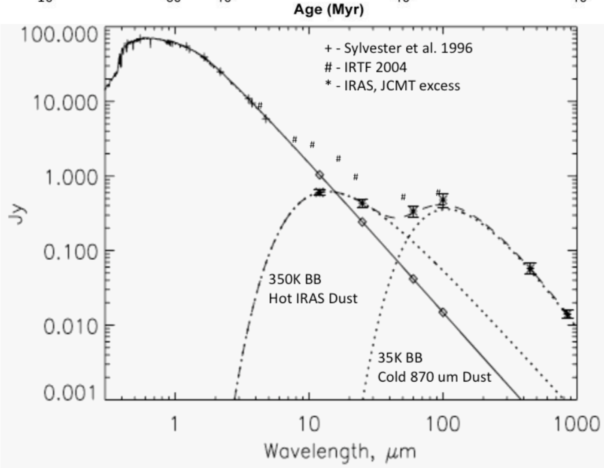
The best-fit model PSD has dn/da ~ $a^{-4.0}$, 1 – 1000 um, fine dust.

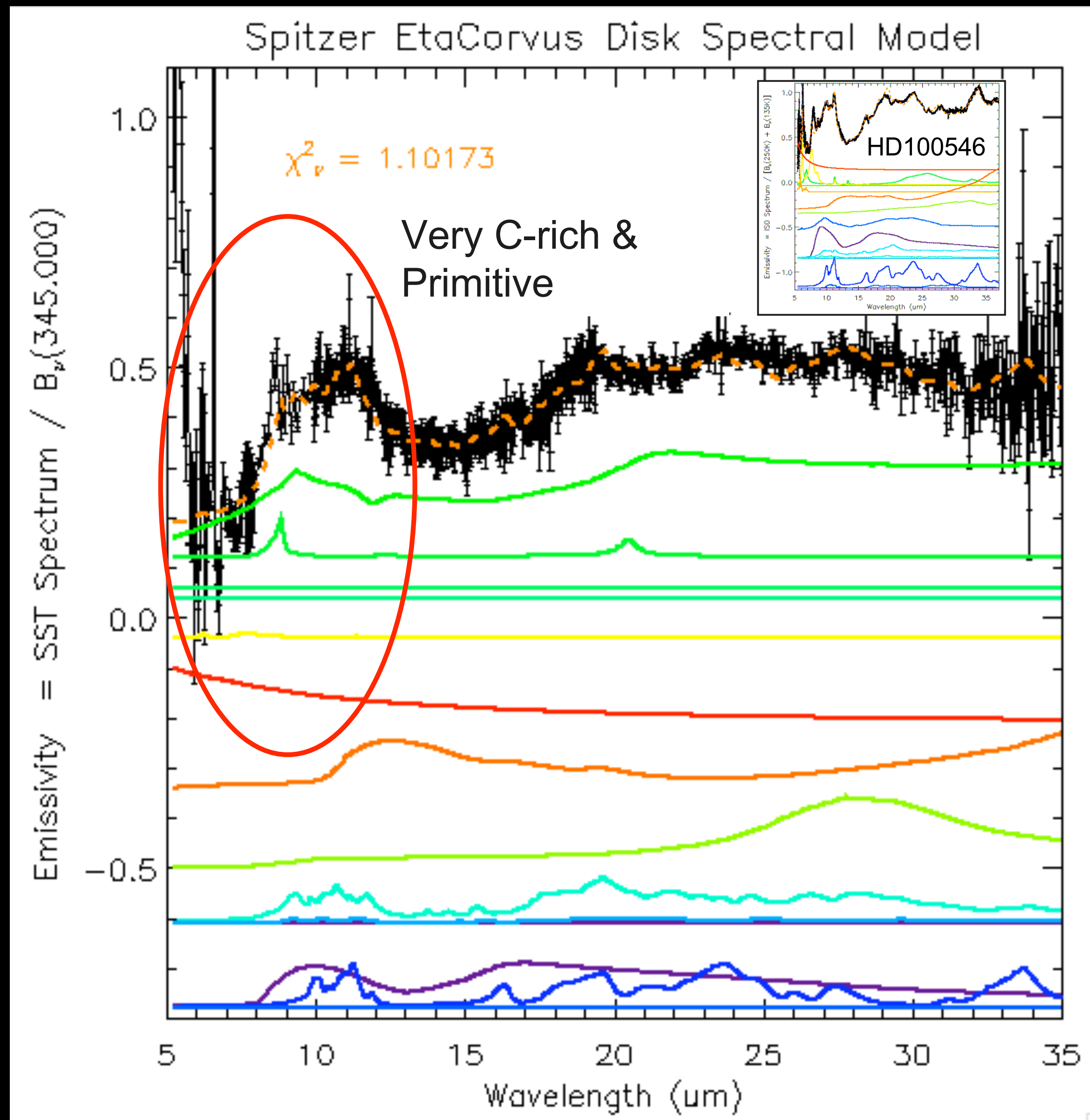
'Mature' Eta Corvus KBO Debris Disk

~1 Gyr F2 @ 18 pc, Hot Dust at 2-3 AU, M_{dust} > M_{pluto}
Excited Kuiper Belt + Cold Dust at ~30K, 0.05 – 0.20 M_{Earth}





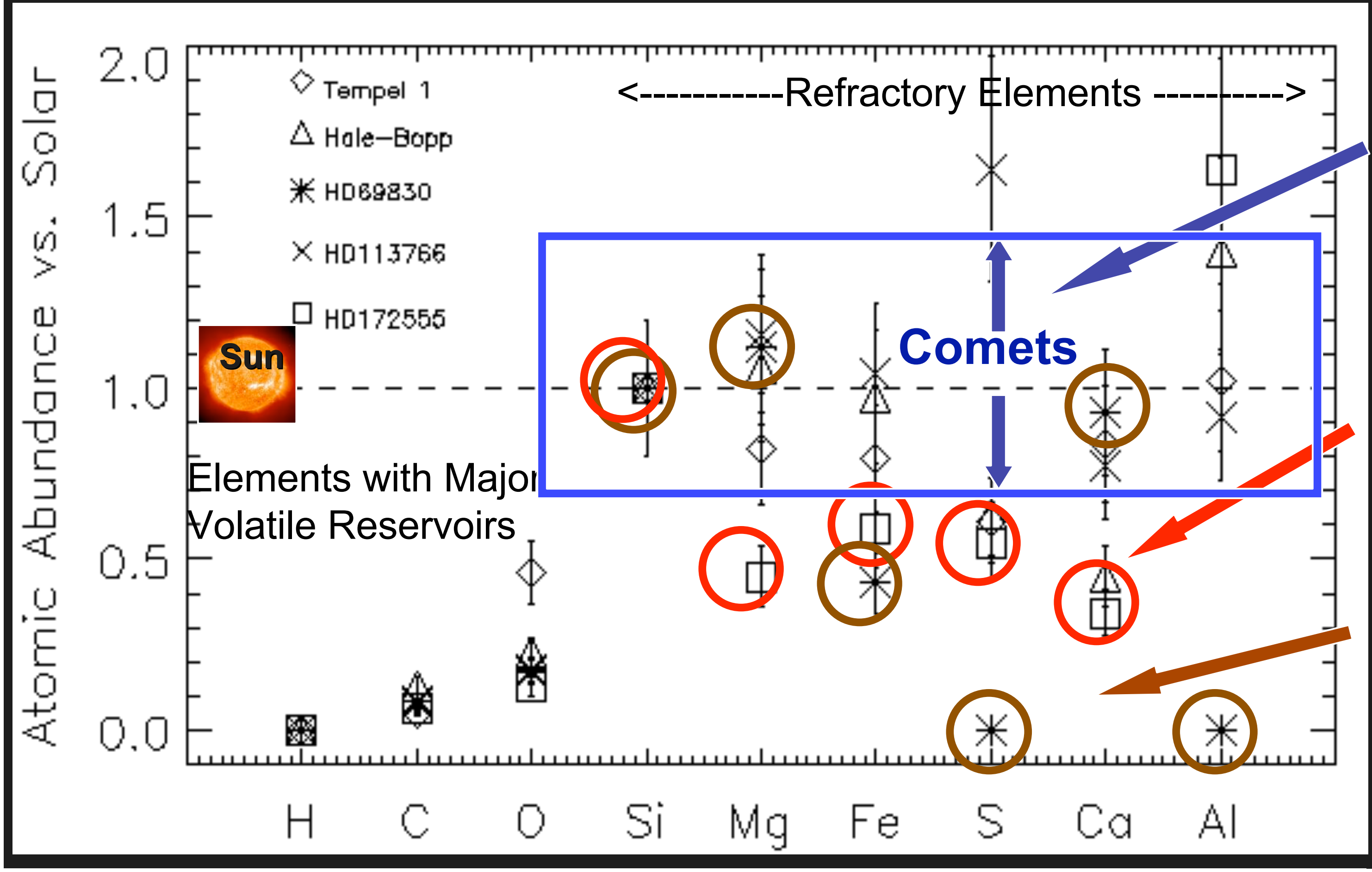




Distingushing Comet, Asteroid, and KBO Dust

Atomic Abundances

Comets, YSOs, and Earth-Building Systems are Near-Solar in Dominant Refractory Elements, but HD69830 asteroidal silicates & HD172555 impact/chondrule silicas are not.



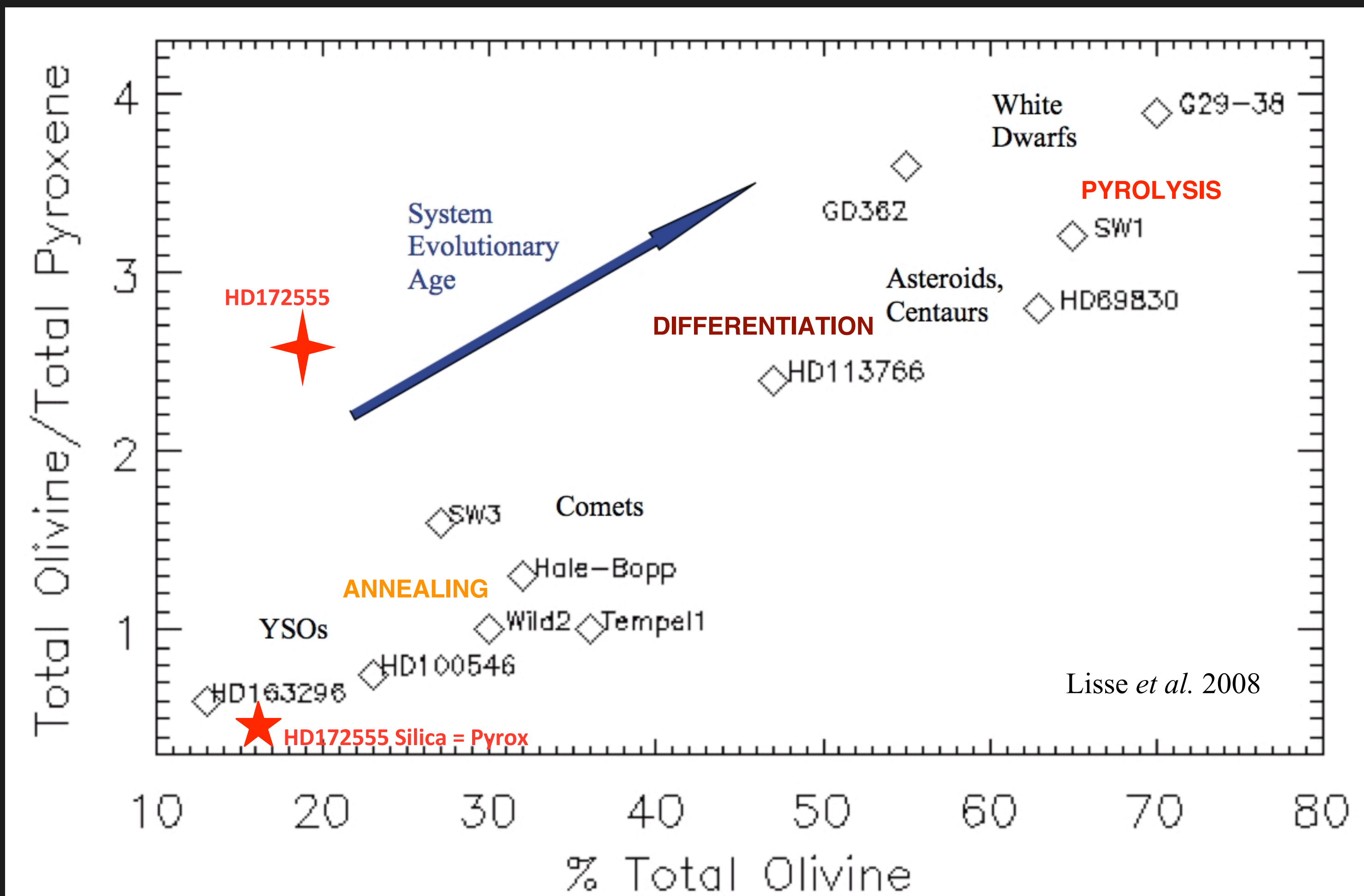
Abundances : Comets are Near-Solar in Dominant Refractory Elements, as is the HD113766 Earth-Building System.

HD172555 Material is strongly depleted in all species except Si and O. Melt and vapor differentiation/ purification?

Main sequence, mature HD69830 P/D type Asteroid Rubble is Not. The composition shows similarity to highly differentiated bodies.

System Silicate Trends

Pyroxenes, abundant in primordial disks and primitive cometary material, appear to be preferentially destroyed as ISM dust becomes more and more crystallized in primordial disks, as olivine grows in differentiated mantles during planet formation, and as WDs further roast the remnant bodies in their systems.



Minimum Total Masses (in beam) for ISO/*Spitzer* and Selected Relevant Solar System Objects

Object	Observer Distance[1] (pc/AU)	Mean Temp[2] (K)	Equiv Radius[3] (km)	19 um Flux[4] (Jy)	Approximate Mass[5] (kg)
Earth	---	282	6380		6×10^{24}
Mars	1.5 AU	228	3400		6×10^{23}
Mercury	0.5-0.7 AU	400	2400		3×10^{23}
HD113766 (F3/F5)	130.9 pc	440	300 – 3000	1.85	$\geq 3 \times 10^{23}$
Moon	0.0026 AU	282	1740		7×10^{22}
HD172555 (A5)	29 pc	335	1000 – 2000		$10^{22} - 10^{23}$
HD10647 (F9)	18 pc	30	(200-2000)	0.015	$\sim 1 \times 10^{23}$
Eta Corvus (F2)	18 pc	280	≥1200		$\geq 2 \times 10^{22}$
HD100546 (Be9V)	103.4 pc	250/135	≥ 910	203	$\geq 1 \times 10^{22}$
Pluto	40 AU	45	1180		1×10^{22}
Asteroid Belt	0.1 - 5.0 AU	Variable			3×10^{21}
Enceladus	10.5 AU	75 – 135	200		1×10^{20}
ID8	450 pc	900	120		3×10^{19}
EF Cha	106 pc	480	120		3×10^{19}
P1121	490 pc	1100	90		8×10^{18}
HD69830	12.6 pc	340	30 - 60	0.11	$3 \times 10^{17} - 2 \times 10^{18}$
GD29-38, G362	13.6 pc	~930	~30	0.005	3×10^{17}
Zody Cloud	0.1 - 4.0 AU	260			4×10^{16}
Asteroid	0.1 - 5.0 AU	Variable	1 - 500		$10^{13} - 10^{21}$
Comet nucleus	0.1 - 10 AU	Variable	0.1-50		$10^{12} - 10^{15}$
Hale-Bopp coma	3.0 AU	200		144	2×10^{9}
Tempel 1 ejecta	1.51 AU	340		3.8	$1 \times 10^{6} - 1 \times 10^{7}$

(1) - Distance from Observer to Object.
(2) - Mean temperature of thermally emitting surface.
(3) - Equivalent radius of solid body of 2.5 g cm^{-3}.
(4) - System or disk averaged flux.
(5) - Lower limits are conservative, assuming maximum particle size of 1000 μm, and ignoring optical thickness effects.
For HD172555, we have included the mass of SiO gas in the estimate. Upper limits assume a maximum particle size of 10m radius.

ZEBRA Design Details

How & What Do We Extract From Mid-IR Spectral Modeling?

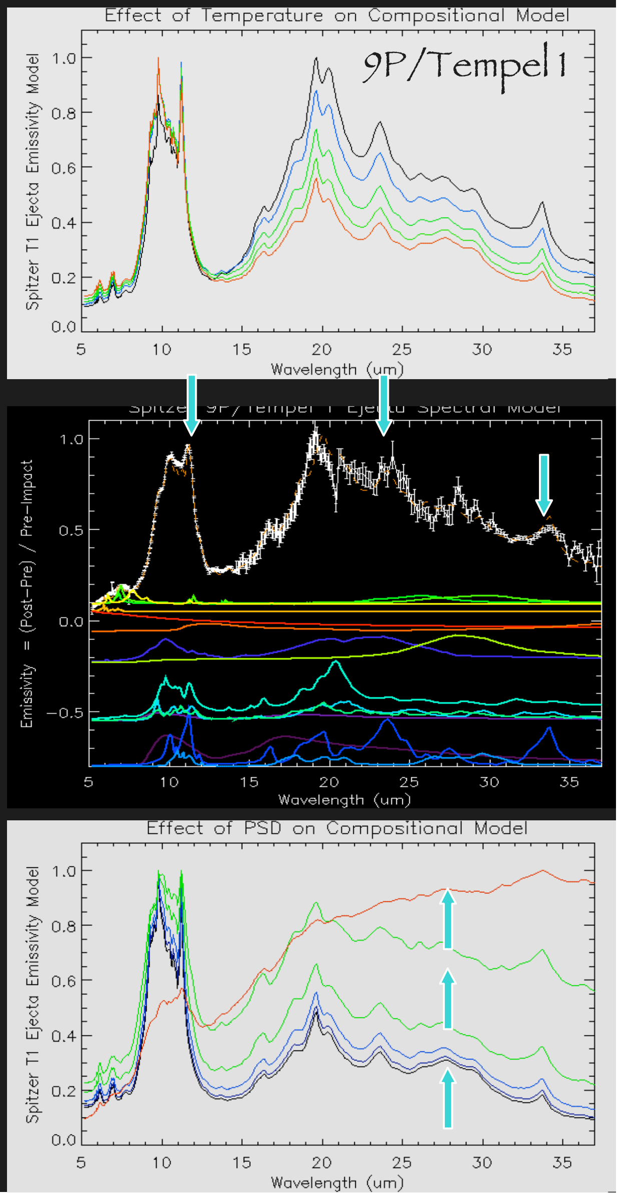
$$F_{\lambda,\mathrm{mod}} = \frac{1}{\Delta^2} \sum_i \int_0^\infty \underbrace{B_\lambda(T_i(a,r_*))}_{(1)} \underbrace{Q_{abs,i}(a,\lambda)\pi a^2}_{(2)} \underbrace{\frac{dn_i(r_*)}{da}}_{(3)} da$$

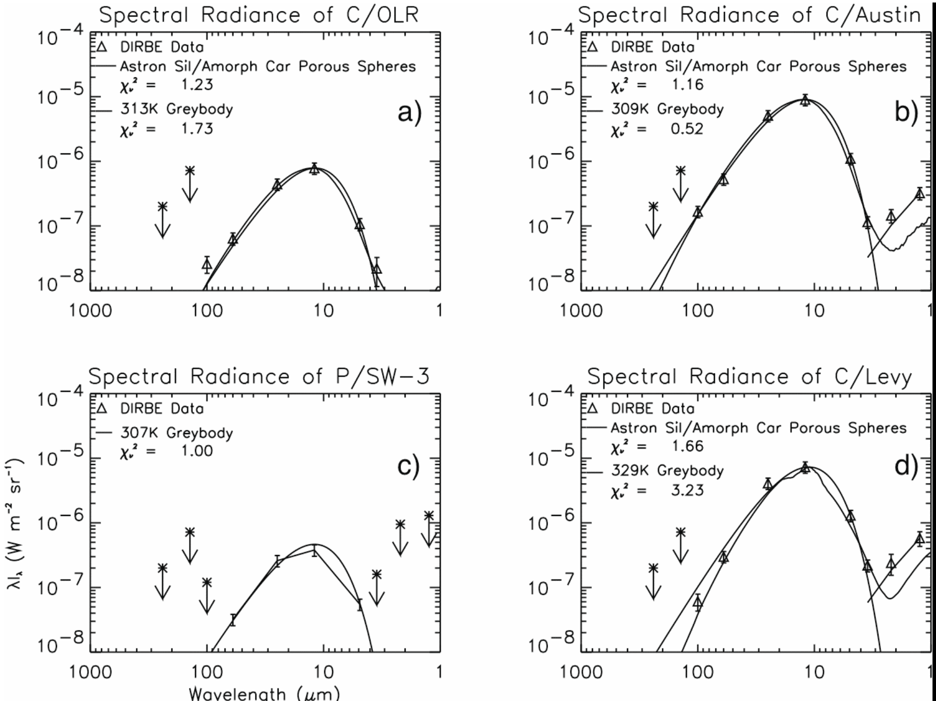
- **(1) Temperature of Dust Components (30 – 1000 K)**
  - Obtained from short/long wavelength amplitude, feature
  - No modeling required fit to flux vs balanced emissivity 10/20um
  - From DI, yields Location of dust in exo-systems from observed T's

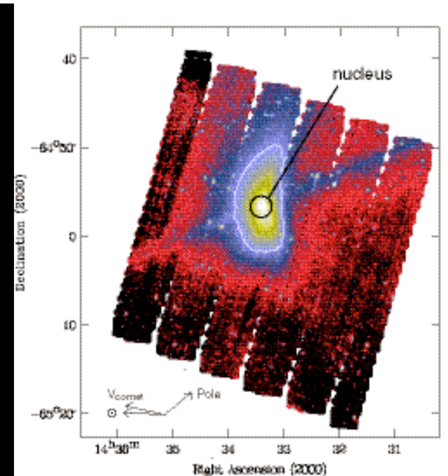
$$T_{dust} = T_{T1ejecta} (L_*/L_{solar})^{1/4} (1.51AU/r_*)^{1/2}$$

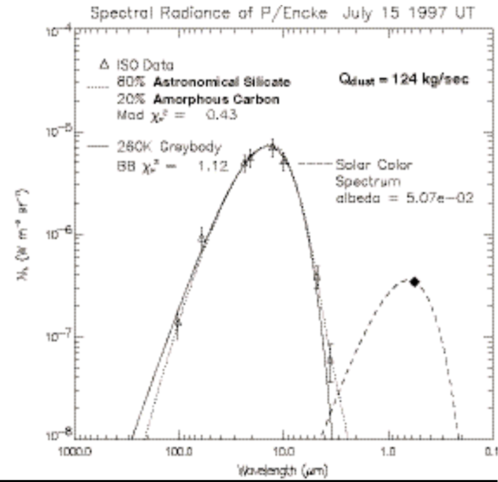
- **(2) Composition & Crystallinity (7 species)**
  - Obtained from strong features at multiple wavelengths
  - Allows search for comparable species in other systems
  - Allows determination of Mineral and Atomic Abundances
  - Allows determination of Crystalline/Amorphous ratio
  - Allows determination of Primitive vs Processed vs Differentiated

- **(3) Particle Size Distribution**
  - Obtained from feature/continuum ratio; dn/da $_{\text{collisional equil}} \approx a^{-3.5}$
  - DI : Unusual narrowly peaked distribution 0.2 - 5 um
  - With distance & abs. flux yields Mass of observed dust (10^6 – 10^{23}kg)
  - Can determine small body vs proto-planet source

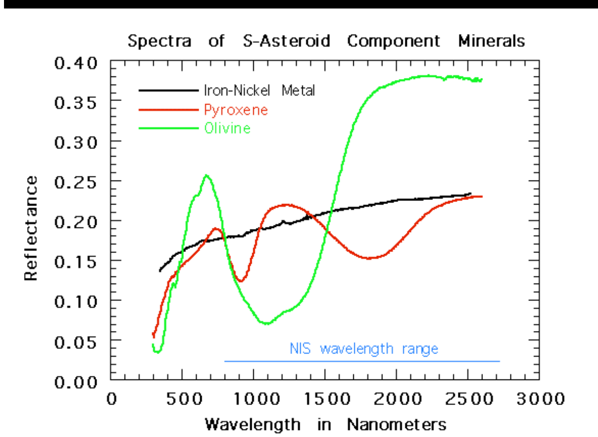


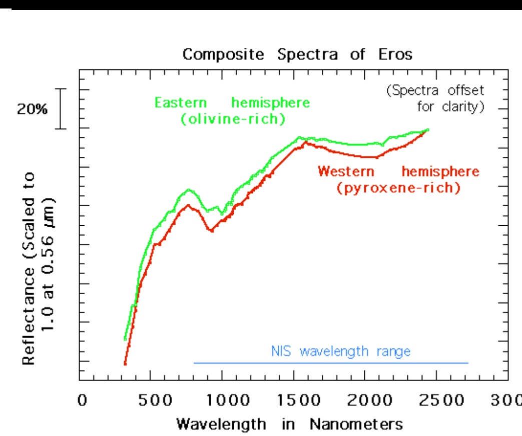


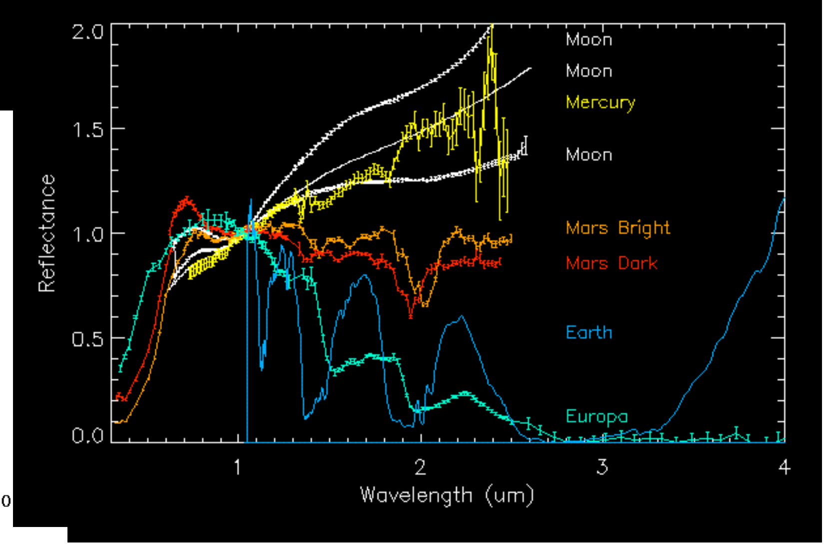




Zody Dust Large, NIR Reflection Spectra Likely Most Diagnostic







How I Would Design ZEBRA

- ZEBRA to view EBL signal from 5 AU, the better to understand & remove Zody = Scatt light (0.1 – 7 um) + Therm Emission (7-10um)
- ZEBRA experiment analogous to flying through a Comet Coma with supporting External Earth-based observations
- Absolute Photometer + Spectrometer – CCD + HgCdTe/Hawaii2R
- VISIR (0.4 – 7.0) [easy] & MIRI (7.0 – 25 um) [hard]
- Maximum Sensitivity for Passive Cooling
- Spectrometer at R=100-200 Good Enough to Find Multiple Spectral Features & Determine Average Composition
- But Thermal Emission Features Weak Due to Large, Opticall Thick Dust
- Zody Science Goals: Determine Olivine/Pyroxine/Ice Ratio; Total Dust Column; Dust Temperature => Allow Better Removal of Foreground
- CML Homework: DI Extrapolated NIR Zody Spectrum

Fin