Kobe International School of Planetary Sciences:
Small Bodies in Planetary Systems
6 December 2006

Dust Models and Optical Properties

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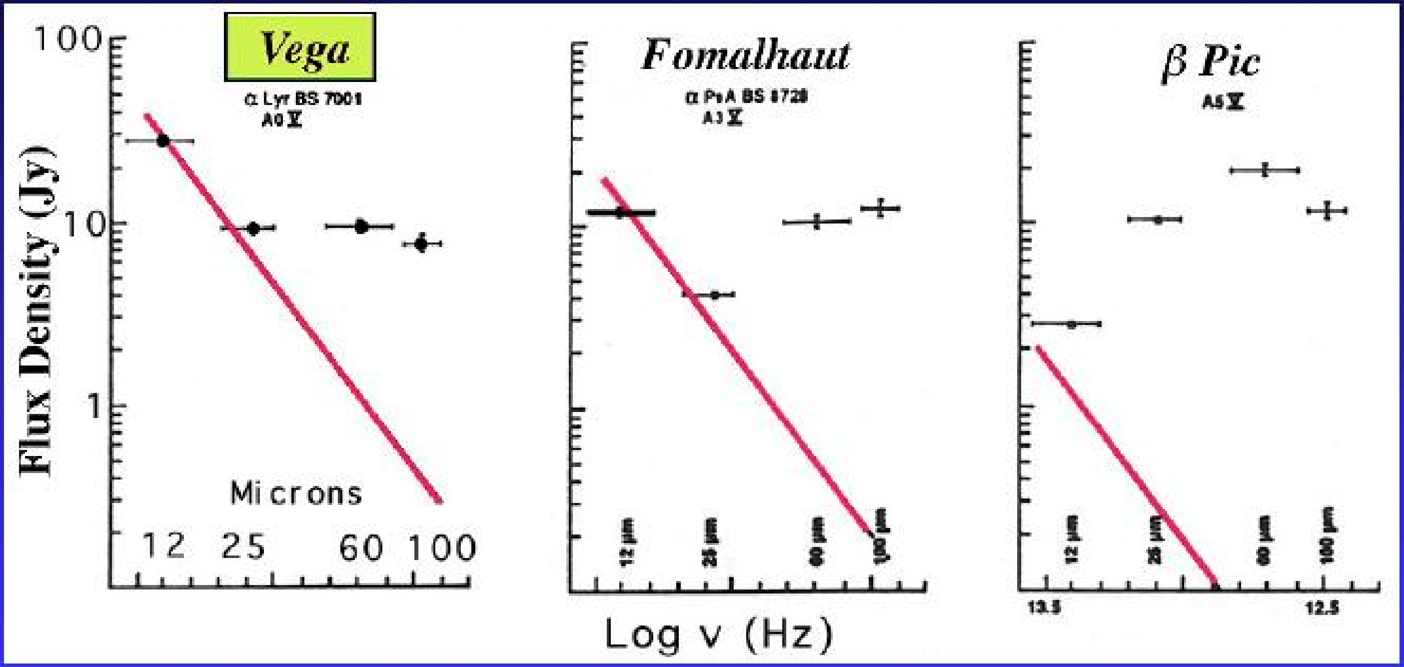
Part III
(2) Dust Disks

- What are debris disks? (MC Wyatt)
- Why are they interesting? (MC Wyatt)
- A porous dust model for debris disks;
- Results for 4 prototypical debris disks;
- Porous aggregate model for cometary dust;

Debris Disks/“Vega-type” Disks

The Vega Phenomenon

The discovery of excess emission from main sequence stars at IRAS wavelengths (Aumann et al. 1984).



Backman & Paresce 1993

"Vega-type" Stars

- "Vega-Phenomenon"
  - Vega: A0V MS star, photometric standard, age ≈ 350Myr;
  - IRAS: IR excess at $\lambda \geq 25\mu m$ (Aumann et al. 1984);

    → black-body $T \approx 85$ K;

    → dust ring at ~ 85 AU;

    → Poynting-Robertson drag ⇨ dust diameter ≥1.2 mm;

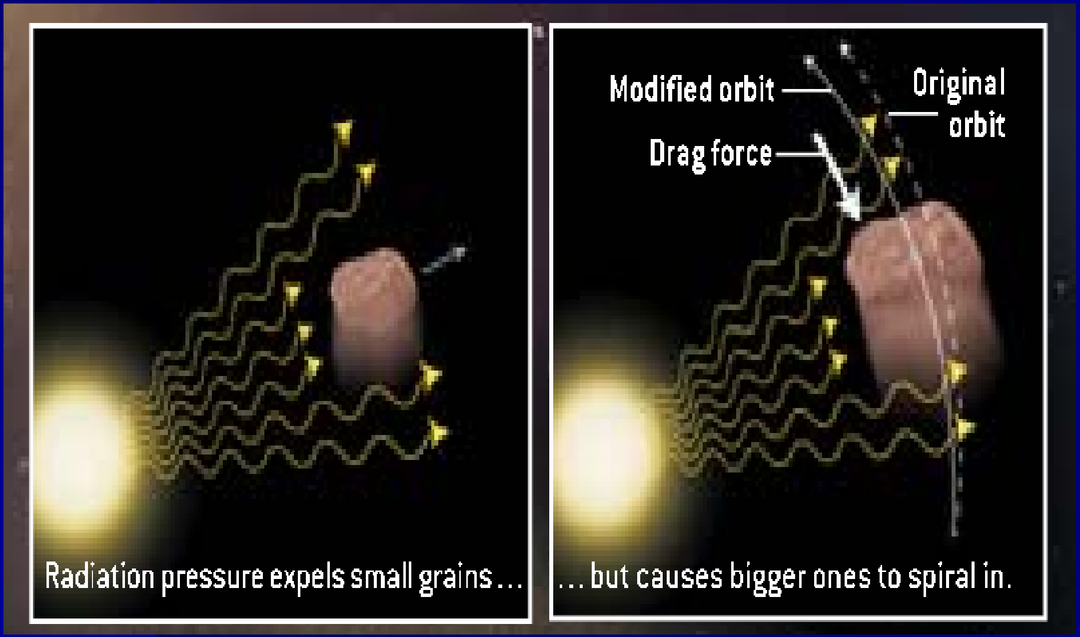
    → $0.012 \leqslant m_{ring}/m_{Earth} \leqslant 300$;
- MS stars with IR-Excess from dust disks: Common!
  - "Big-Four" ⇨ Vega, Fomalhaut, β Pictoris, ε Eridani (Gillett 1986);
  - ≥15% A-K stars with disks!

“Vega-type” Disks: Debris Disks!

- Primordial or 2nd generational?
  - Radiation pressure → dust expulsion;
  - Poynting-Robertson drag → dust spiraling in;
  - Rad-Prs, P-R drag timescale « stellar age

⇨ 2nd generational!

⇨ Require replenishment!



Radiation pressure expels small grains… …but causes bigger ones to spiral in.

Astrophysical Significance

- Debris disks: a signpost for the existence of extrasolar planetary systems!
  - – Planets formed out of protoplanetary dust disks;
  - – Density variations in debris disks (cavities, clumps, warps, rings etc) ⇨ the presence of planets;
- IR emission (images, SED) & dust properties
  - – ⇨ infer disk structures, dust properties;
  - – ⇨ infer disk lifetime ⇨ planetary formation processes at young ages; the presence of comets/asteroids/planetesimals;
  - – IR spectral features ⇨ the formation of comets and/or planetesimals;

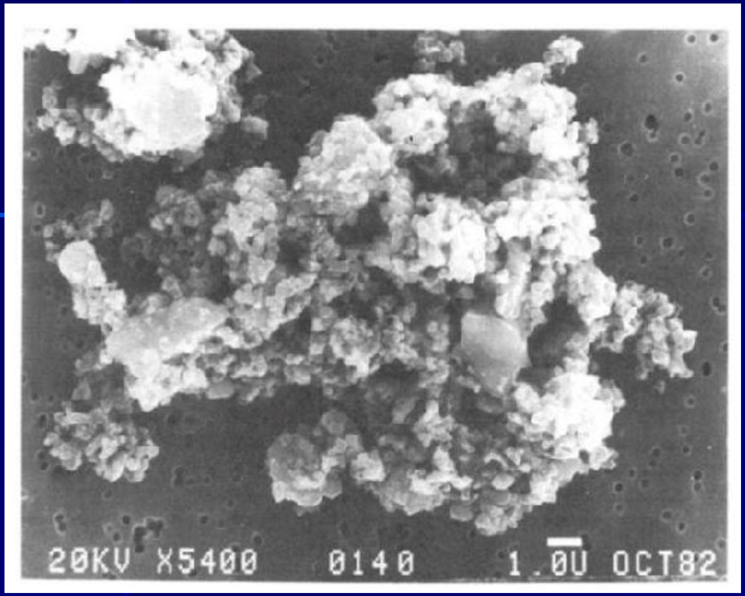
Astrophysical Significance

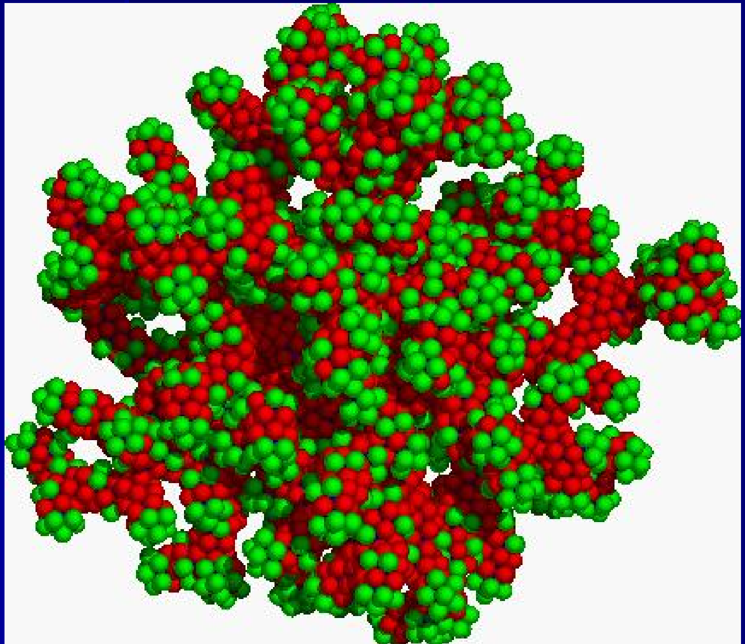
- To understand the formation process of planetary systems ⇨ need to understand the physical, chemical and dynamical properties of circumstellar disks and their constituent dust grains ⇨ need a working dust model!
- Key elements for a dust model for debris disks:
  - Morphology;
  - Chemical composition;
  - Size distribution;
  - Spatial distribution;

Dust Sources for Debris Disks

- Collisional grinding down of asteroidal bodies;
- Evaporation of cometary bodies;

A Porous-Dust Model for Dust Disks





- Interplanetary Dust Particles: fluffy structure, density 2 g/cm^3 → porosity $P=V_{vacuum}/V_{tot} \sim 0.4$ (Brownlee 2003);
- Cometary nuclei: density 0.5 g/cm^3 → $P \sim 0.9$ (Rickman 2003; Whipple 1999) for cometary dust;
- Dust coagulation experiments → $0.8 \leqslant P \leqslant 0.93$ (Blum et al. 2003);
- Dust coagulation modeling → $0.85 \leqslant P \leqslant 0.95$ (Cameron & Schneck 1965; Henning et al. 2003);
- ⇨ Morphology: fluffy dust with $P=0.9$;

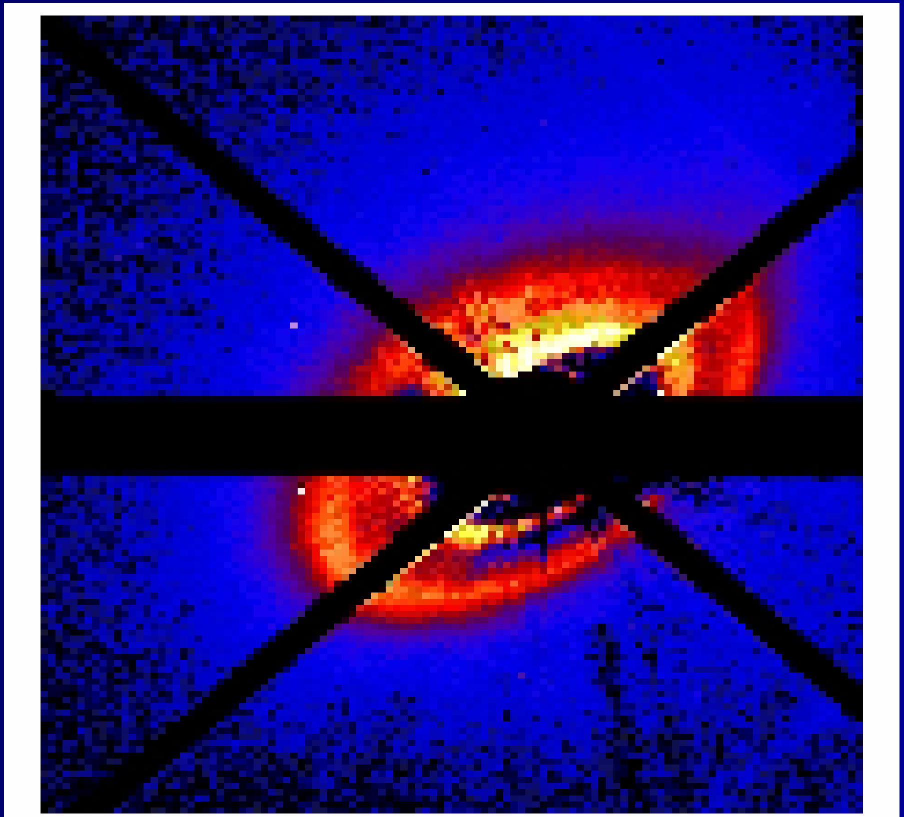
Dust Composition and Sizes

- Composition: porous aggregates of unaltered or significantly-modified interstellar silicate, carbon and ice grains;
- Size distribution: $dn(a)/da \sim a^{-q}$;
  - ⇨ $1\mu m \leqslant a \leqslant 1cm$;
- Dust Spatial distribution $dn(r)/dr$: images of
  - ⇨ optical/near-IR scattered starlight;
  - ⇨ mid-IR/submm dust thermal emission;

Mie theory + Effective Medium Theory ⇨ $Q_{abs}(\lambda)$;

HD141569A

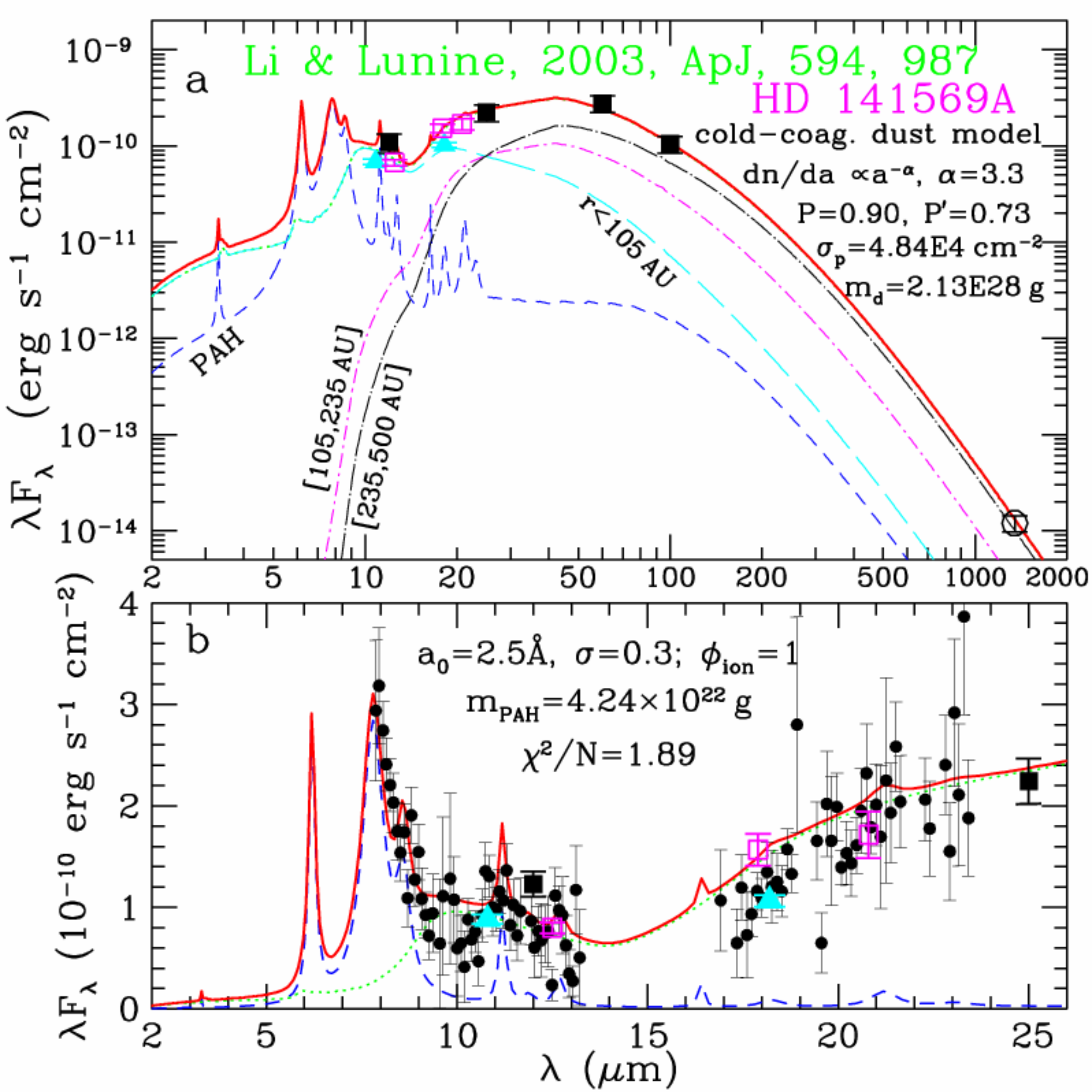
- Pre-MS Herbig Ae/Be star, age ~5 Myr, B9.5V, $T_{eff}\approx10000K$, d≈99pc, $L_* \approx 22.4L_\odot$, inclination 62°;
- 2 rings at 200, 325AU (Augereau et al. 1999, Weinberger et al. 1999, Mouillet et al. 2001);
- Fisher et al. (2000): a 3rd ring at <100AU, ⇨ 10.8, 18.2μm emission;



HD 141569

Results: HD141569A

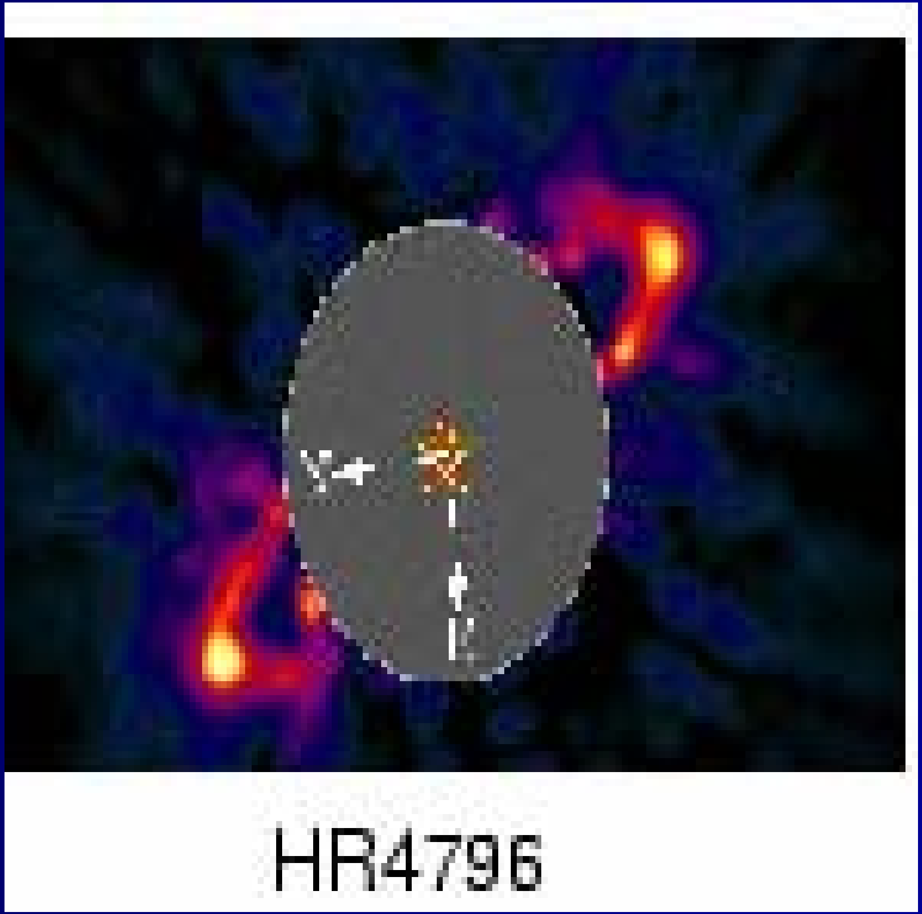
(Li & Lunine 2003, ApJ, 594, 978)



- Model Parameters
  - P=0.90;
  - dn/da ~ $a^{-3.3}$;
  - dn/dr: near-IR, mid-IR imaging → 3 “ring-like” components;
  - PAHs;
- Results
  - m_d≈ 3.6 m_{Earth}, m_{PAH} ≈ 7E-6 m_{Earth};
  - dm_d/dt: RadPr≈8E-6, PR≈1.4E-8 m_{Earth}/yr;
  - total supply 39m_{Earth};

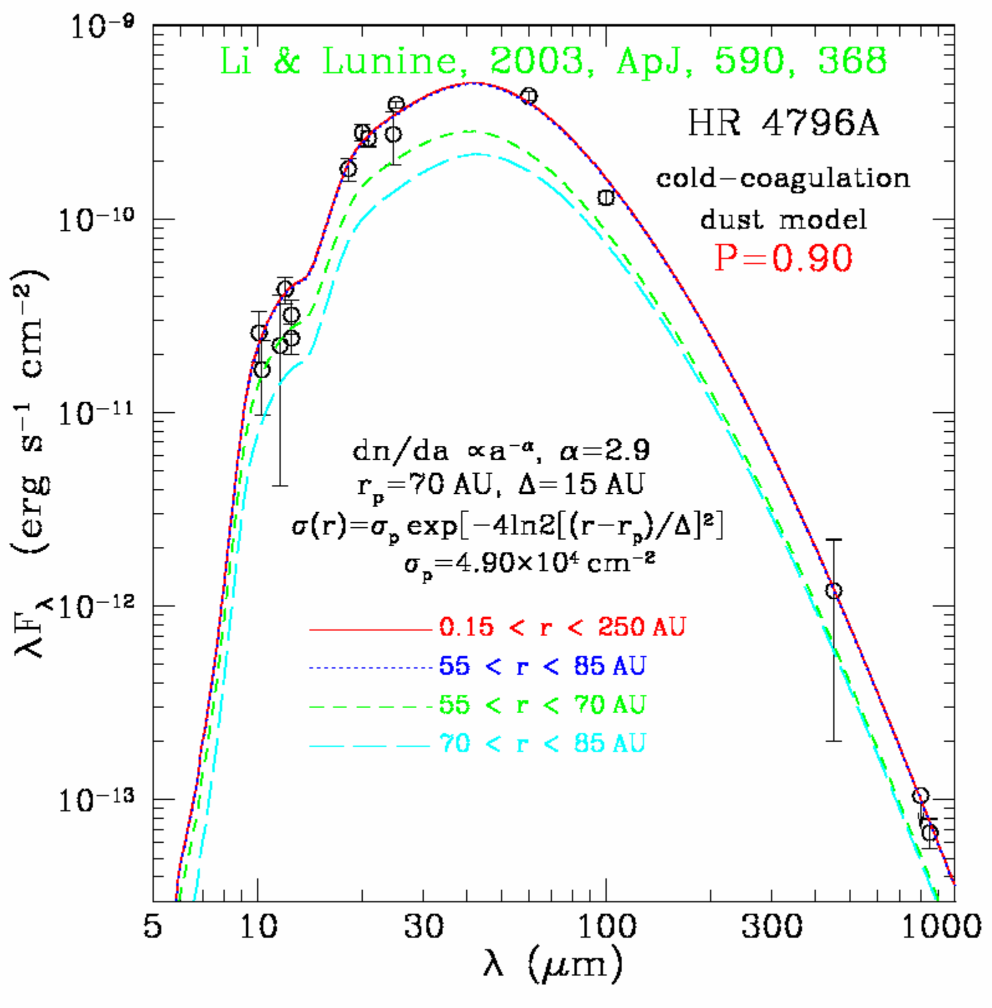
HR 4796A

- Young MS A0V star, age ~8Myr, $T_{eff} \approx 9500K$, d≈67pc, $L_* \approx 21L_\odot$, inclination 27°;
- A sharp ring at ~70AU with FWHM $\leqslant$17AU (Schneider et al. 1999, Telesco et al. 2000);



Results: HR4796A

(Li & Lunine 2003, ApJ, 590, 368)

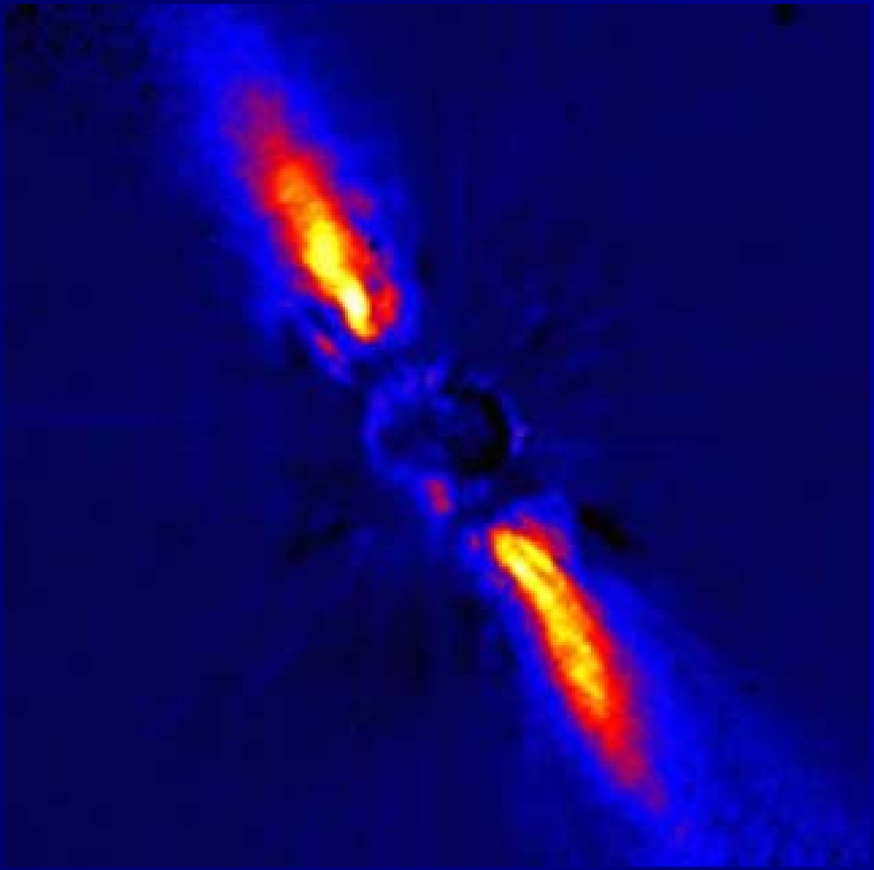


- Model Parameters
  - P=0.90;
  - dn/da ~ $a^{-2.9}$;
  - dn/dr: near-IR, mid-IR imaging

    → a sharp ring;
- Results
  - $m_d \approx 0.7 m_{Earth}$;
  - dm_d/dt: RadPr≈8E-7, PR≈9E-9 m_{Earth}/yr;
  - total supply $6.7 m_{Earth}$;

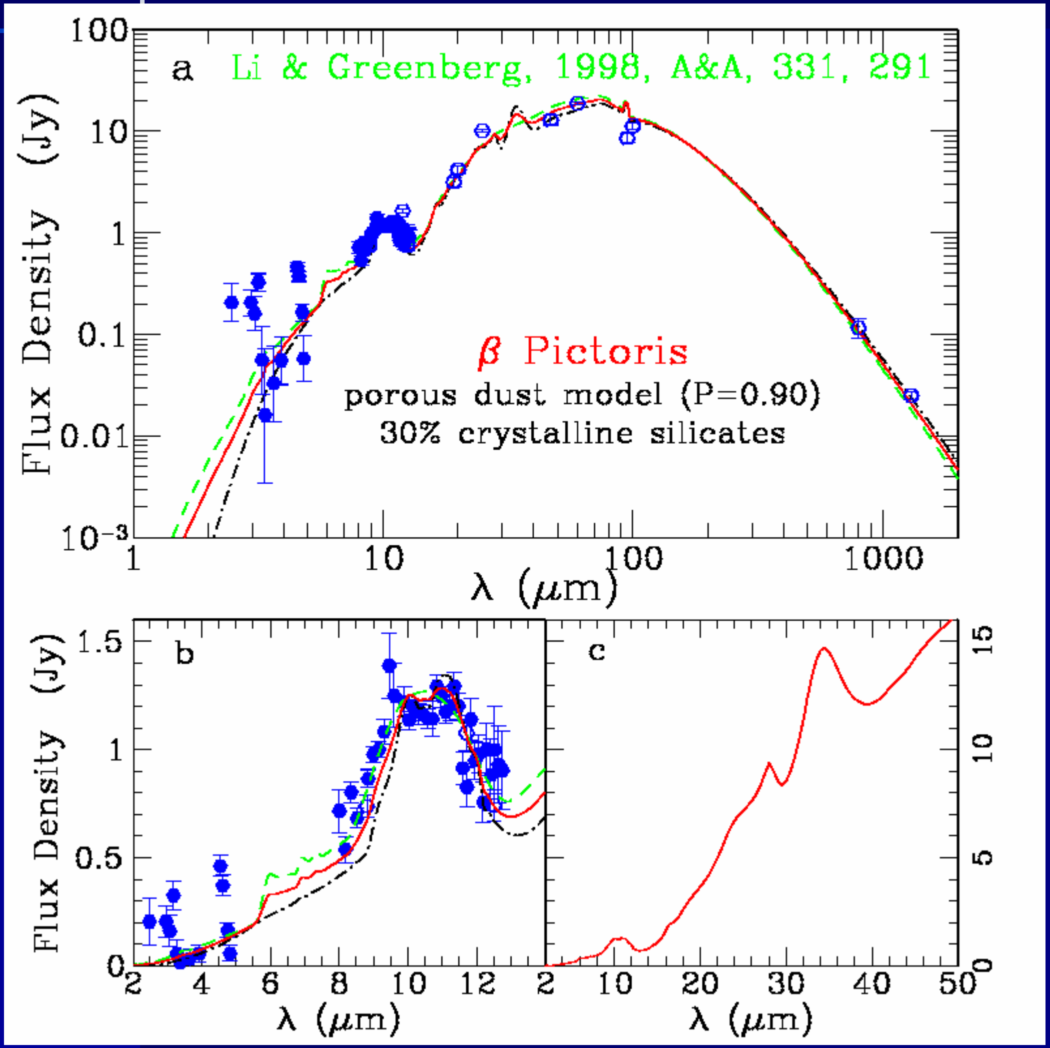
β Pictoris

- MS A5V star, age ~15Myr, T_{eff}≈8200K, d≈19.3pc, $L_* \approx 9L_\odot$;
- An extended (>1000AU) edge-on disk (Smith & Terrile 1984; Mouillet et al. 1997; Holland et al. 1998);



Results: β Pictoris

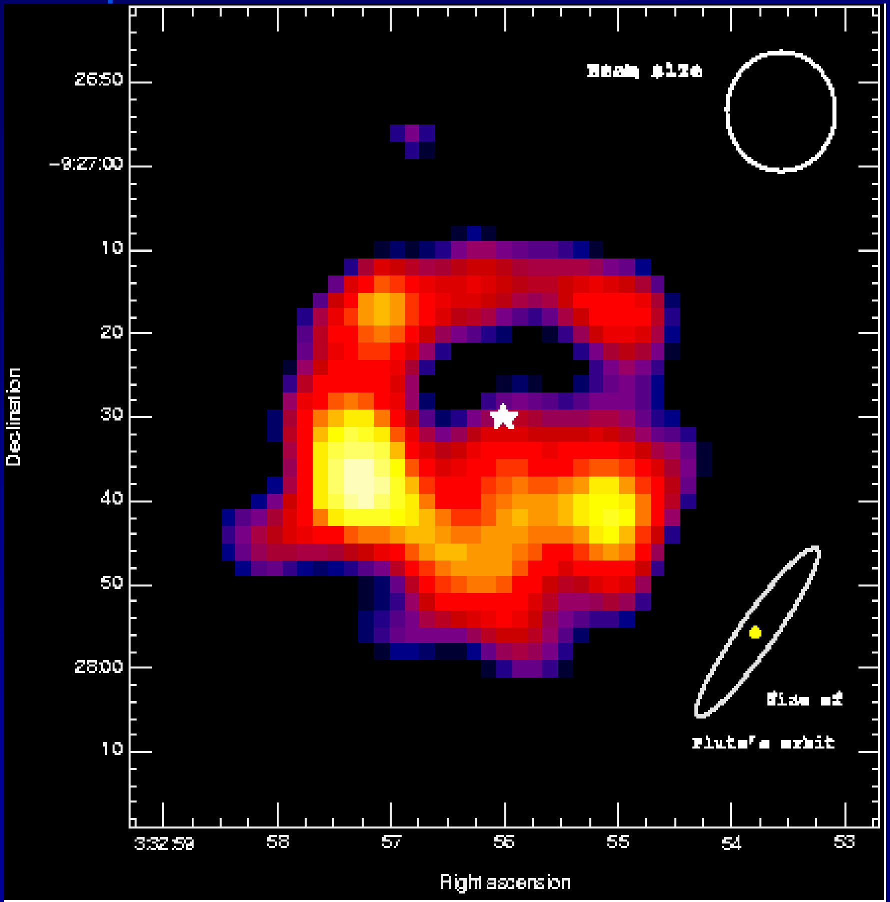
(Li & Greenberg 1998, A&A, 331, 291)

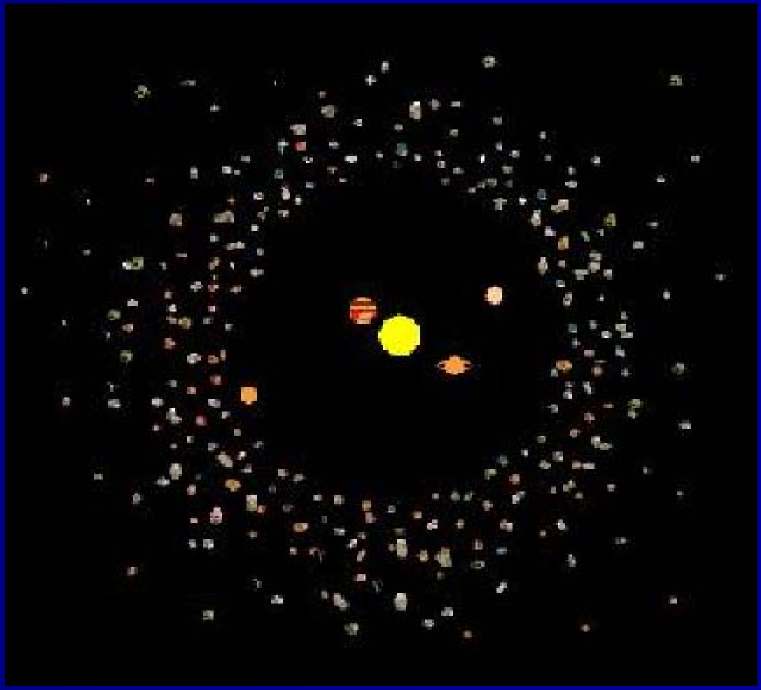


- Model Parameters
  - P=0.90;
  - dn/da ~ $a^{-2.9}$;
  - dn/dr: optical imaging;
- Results
  - $m_d \approx 0.4 m_{Earth}$;
  - 30% crystalline silicates;

ε Eridani

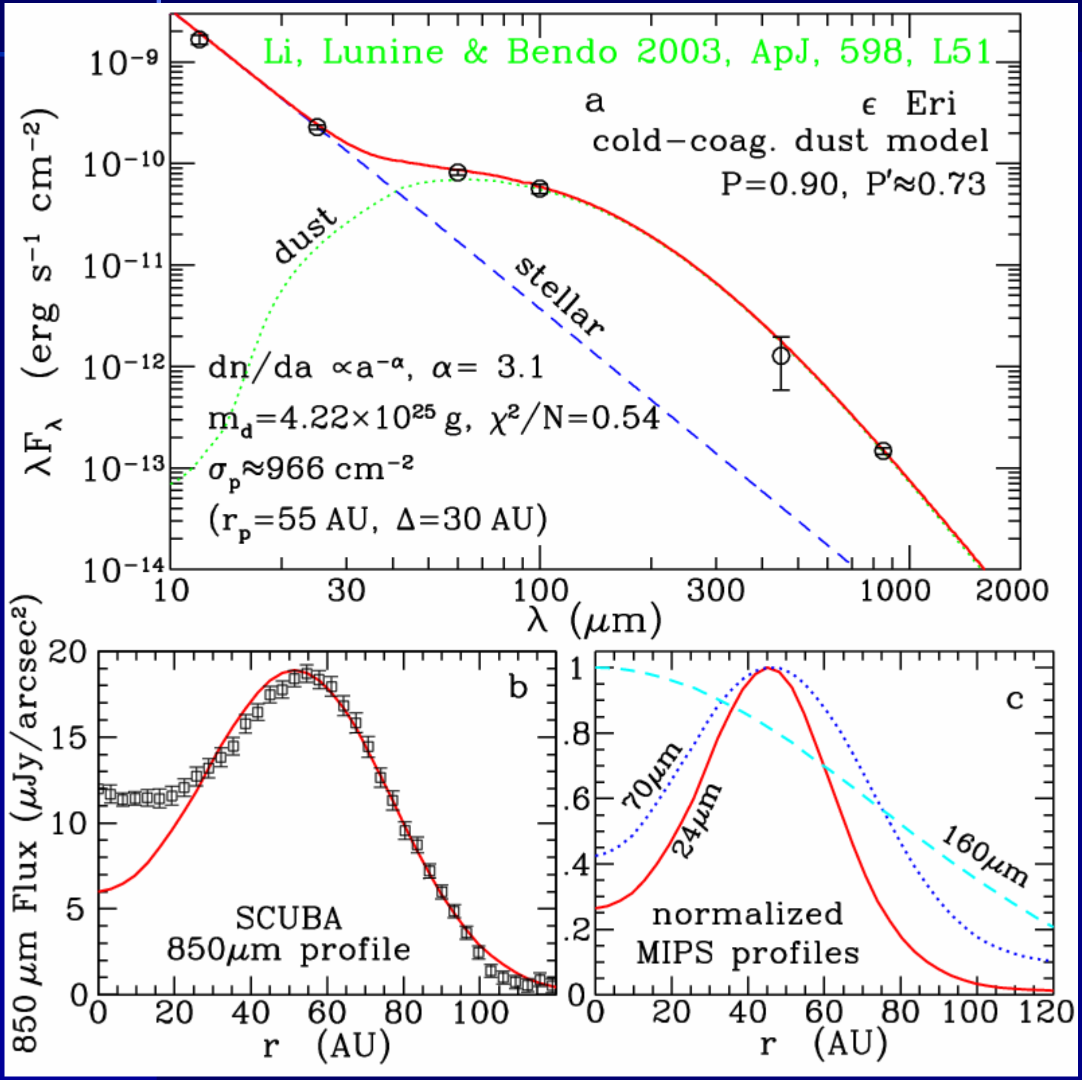
- MS K2V, age ~800Myr, T_{eff}≈5000K, d≈3.2pc, $L_* \approx 0.33L_\odot$;
- A (nearly) face-on ring at ~60AU; a central cavity at ~30AU (Greaves et al. 1998);
- A Jupiter-mass planet (~6.9yr);





Results: ε Eridani

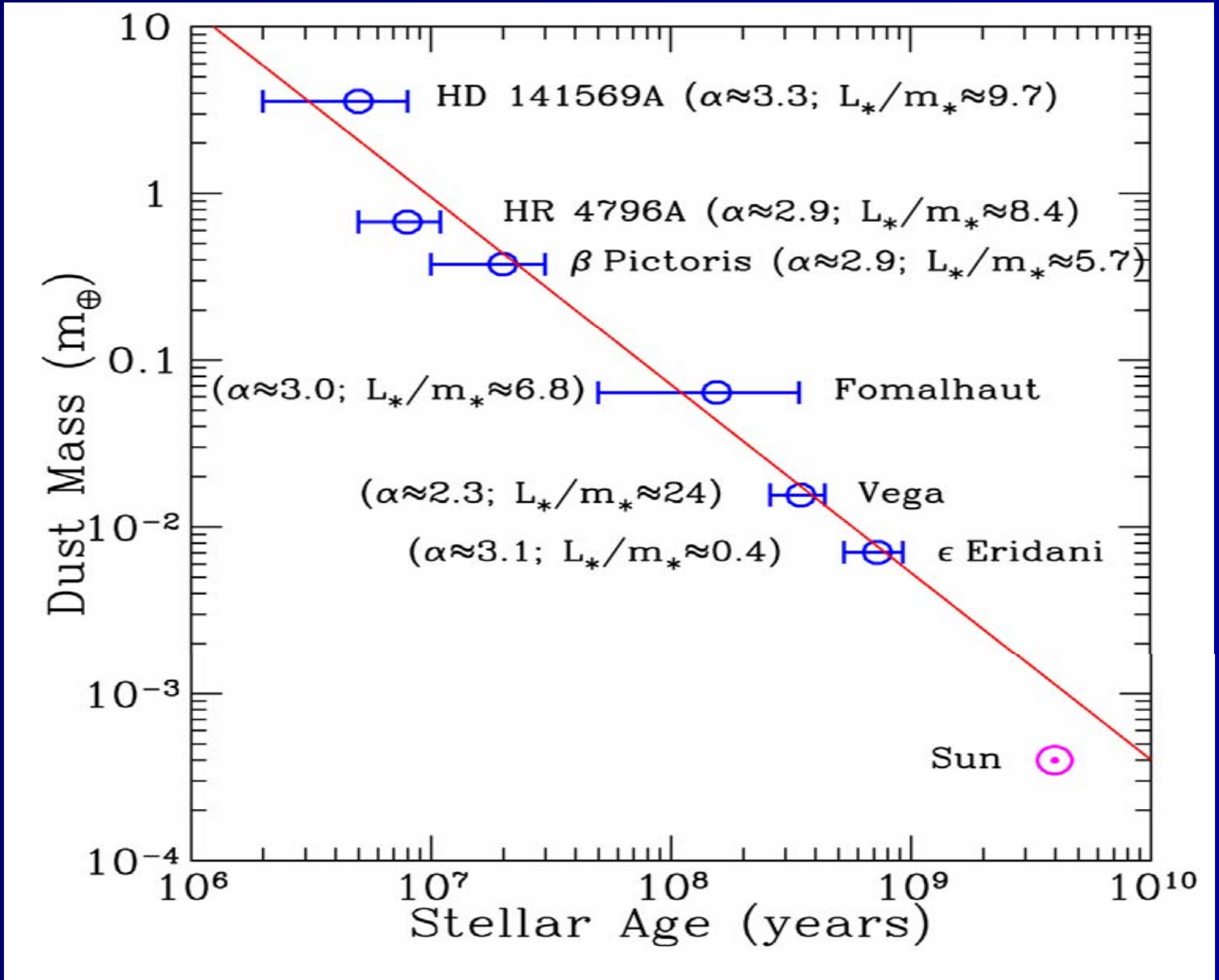
(Li, Lunine, & Bendo, 2003, ApJ, 598, L51)



- Model Parameters
  - P=0.90;
  - dn/da ~ $a^{-3.1}$;
  - dn/dr: submm imaging;
- Results
  - $m_d \approx 7E\text{-}3 m_{Earth}$;

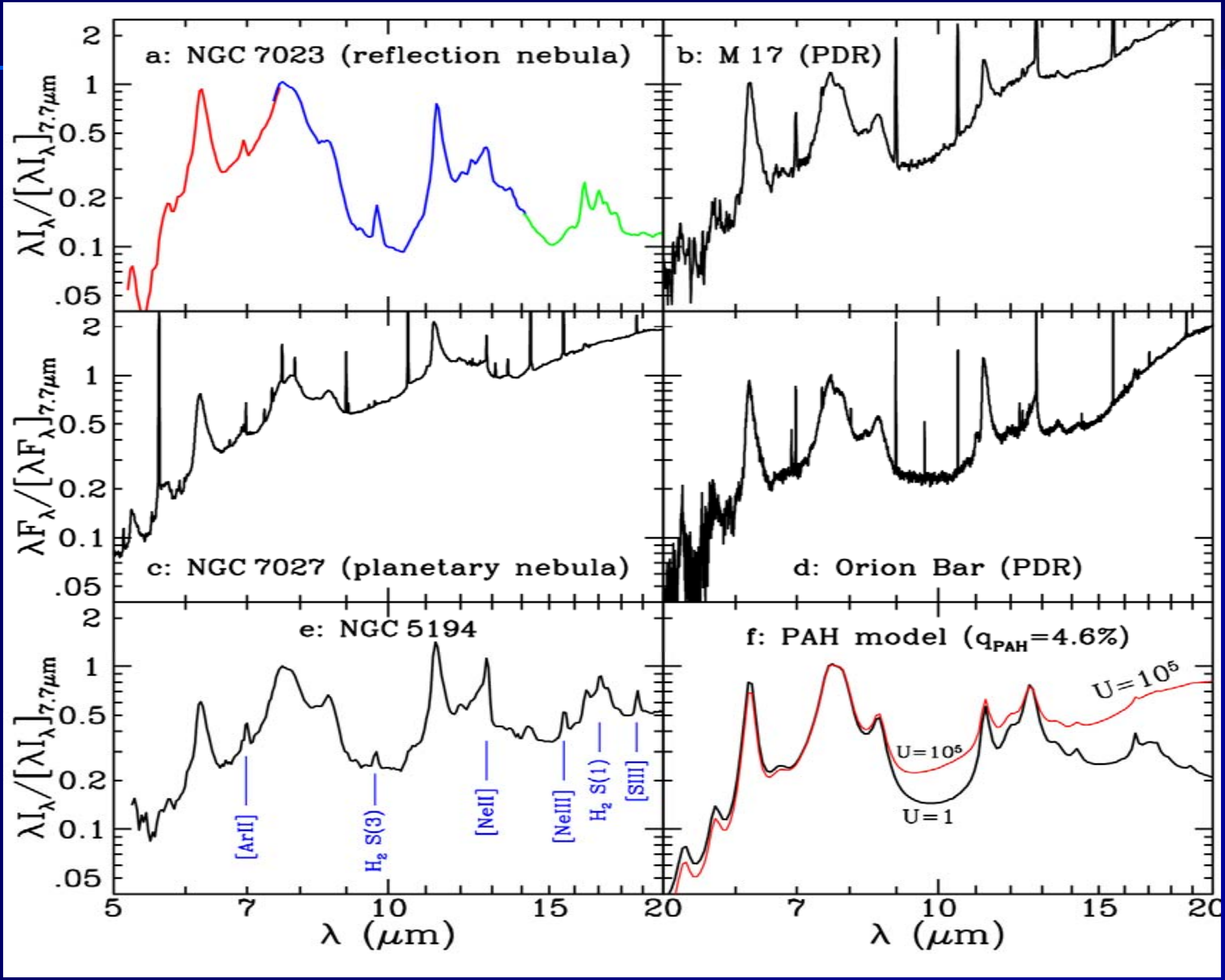
Disk Mass Evolution

- M_d decreases with age (Li, Bendo, & Lunine 2004);



PAHs are ubiquitous in space

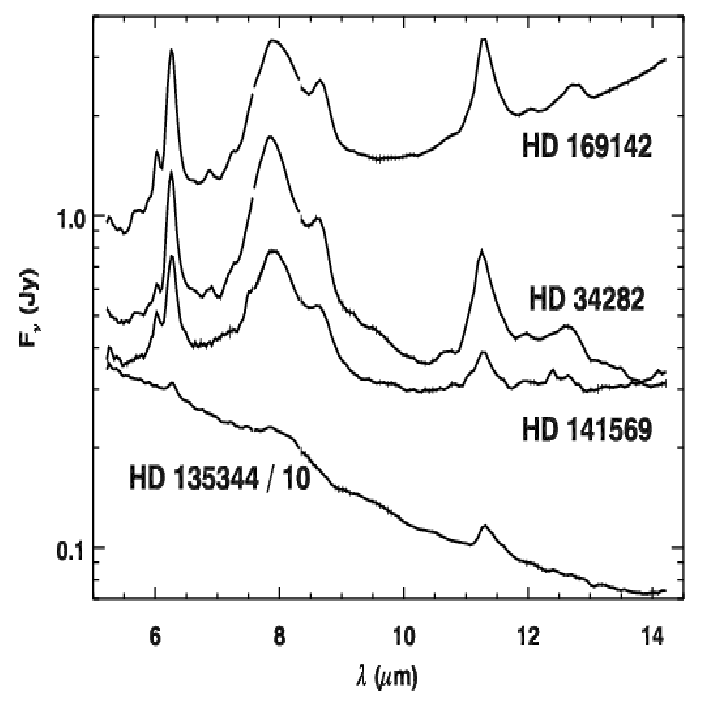
(Draine & Li 2006)



Why Do We Care about PAHs in Dust Disks?

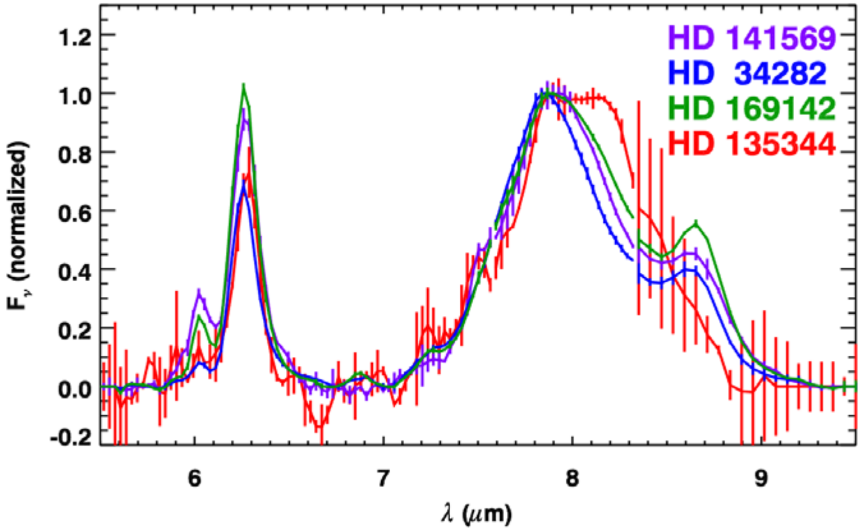
- Emission features of PAHs: tracers of small grains ⇨ diagnostics of grain settling and/or coagulational growth in disks ⇨ process of planetary formation;
- Photoelectrons of PAHs: heating the gas;
- Large surface areas of PAHs, electrons ⇨ play an important role in disk astrochemistry;

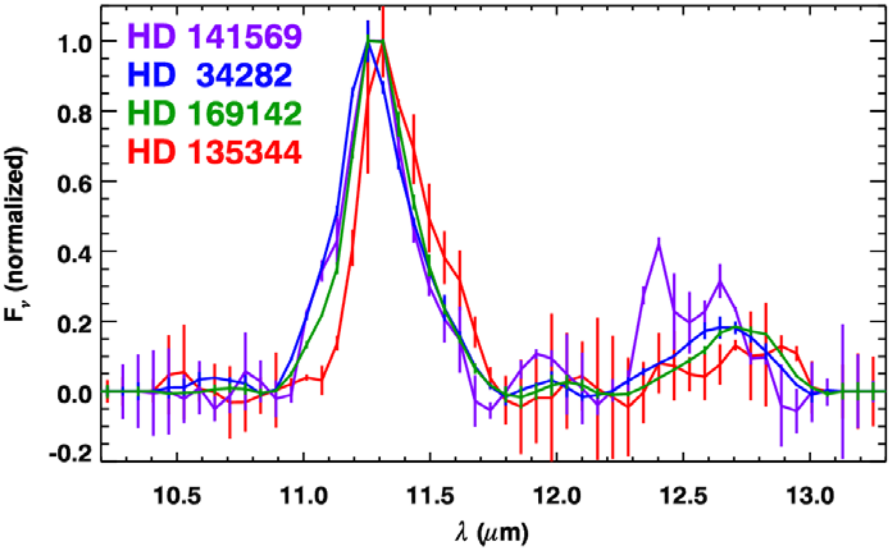
PAHs in Protoplanetary Dust Disks around Herbig Ae/Be Stars

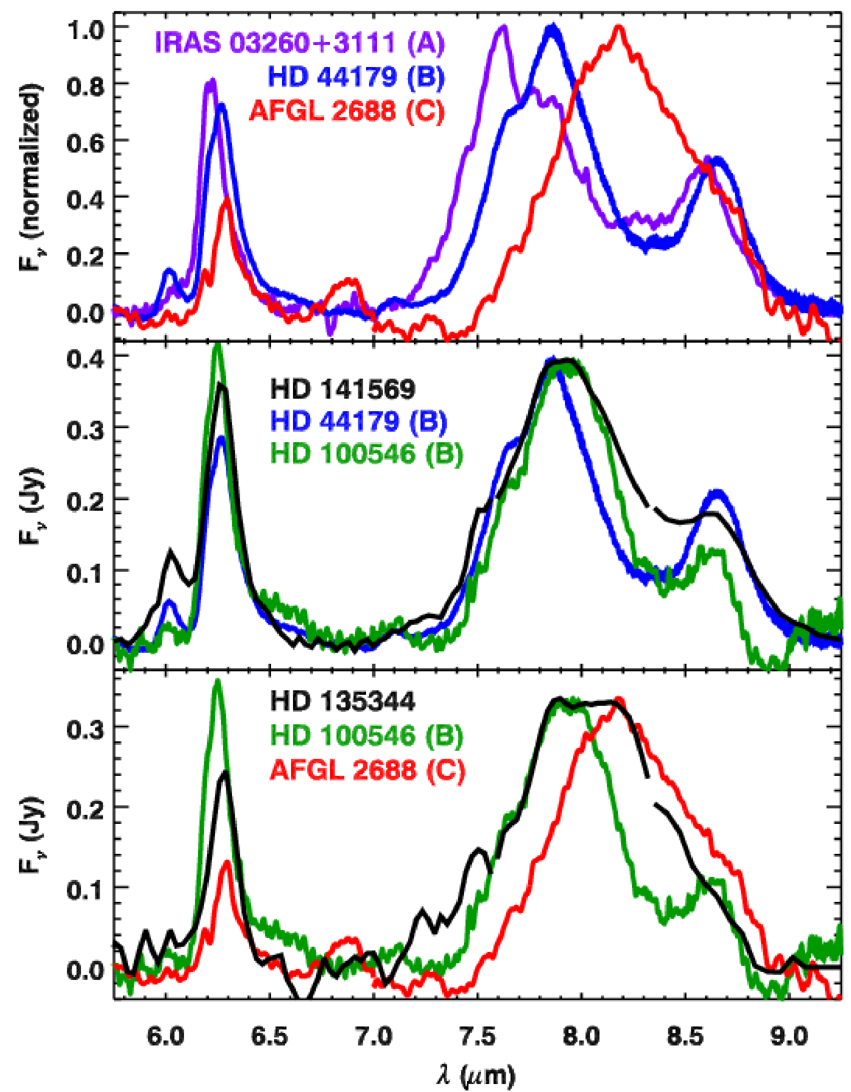


- Herbig Ae/Be Stars: young intermediate 2-8$M_{\odot}$ pre-main sequence stars;
- Ground-based and space-borne spectra → Brooke et al. (1993) detected the 3.3μm C-H stretching feature in ~20% of 42 HAeBe stars;
- ISO spectra → Acke & van den Ancker (2004) reported PAH spectra in ~57% of 46 HAeBe stars;
- Spitzer → Sloan et al. (2005) and Keller et al. (2005);

PAHs in HAeBe Disks:
Spectral variations (Sloan et al. 2005)

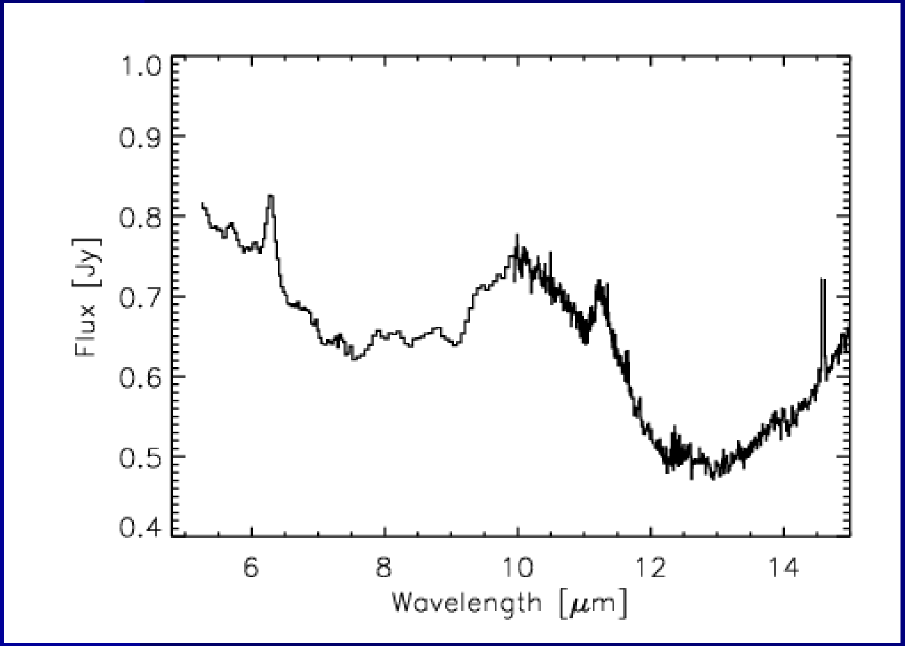


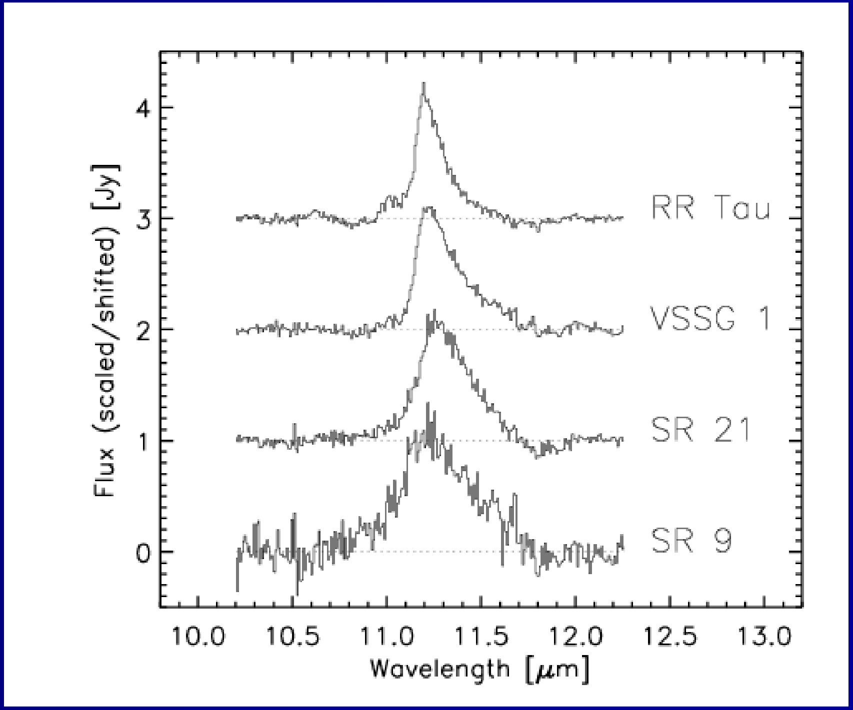




PAHs in Protoplanetary Disks around T Tauri Stars

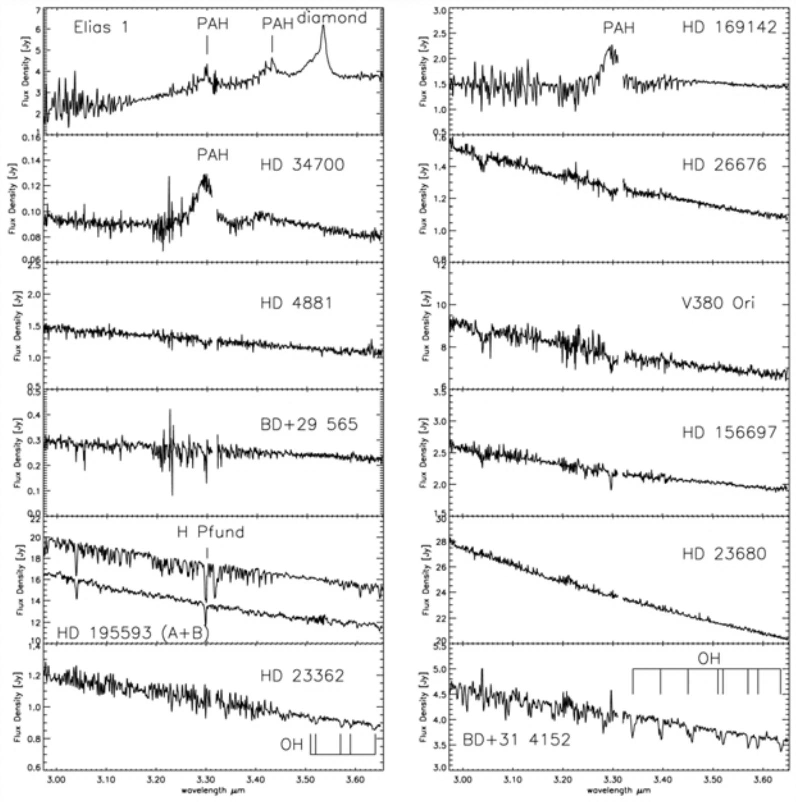
- T Tauri Stars: low-mass pre-MS stars;
- Spitzer → Geers et al. (2005);
- LkHalpha: very different PAH spectrum!





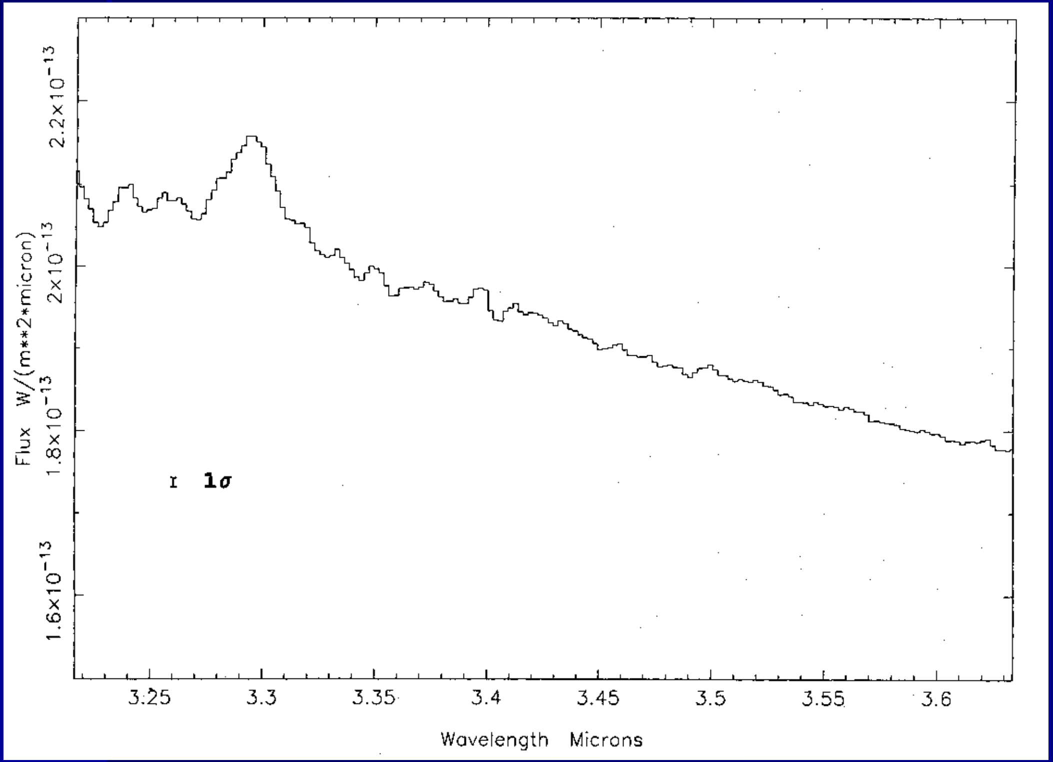
PAHs in Planetary Disks around Vega-type Stars

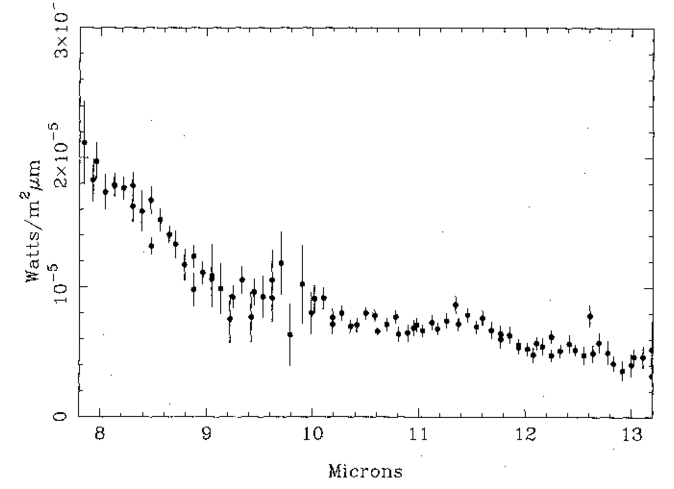
- HD34700: G0V, T_eff=5940K (Smith et al. 2004);
- F, G type stars: lack of ultraviolet photons!
- How are PAHs excited? Do not need energetic photons?



PAHs in Planetary Disks around Vega-type Stars

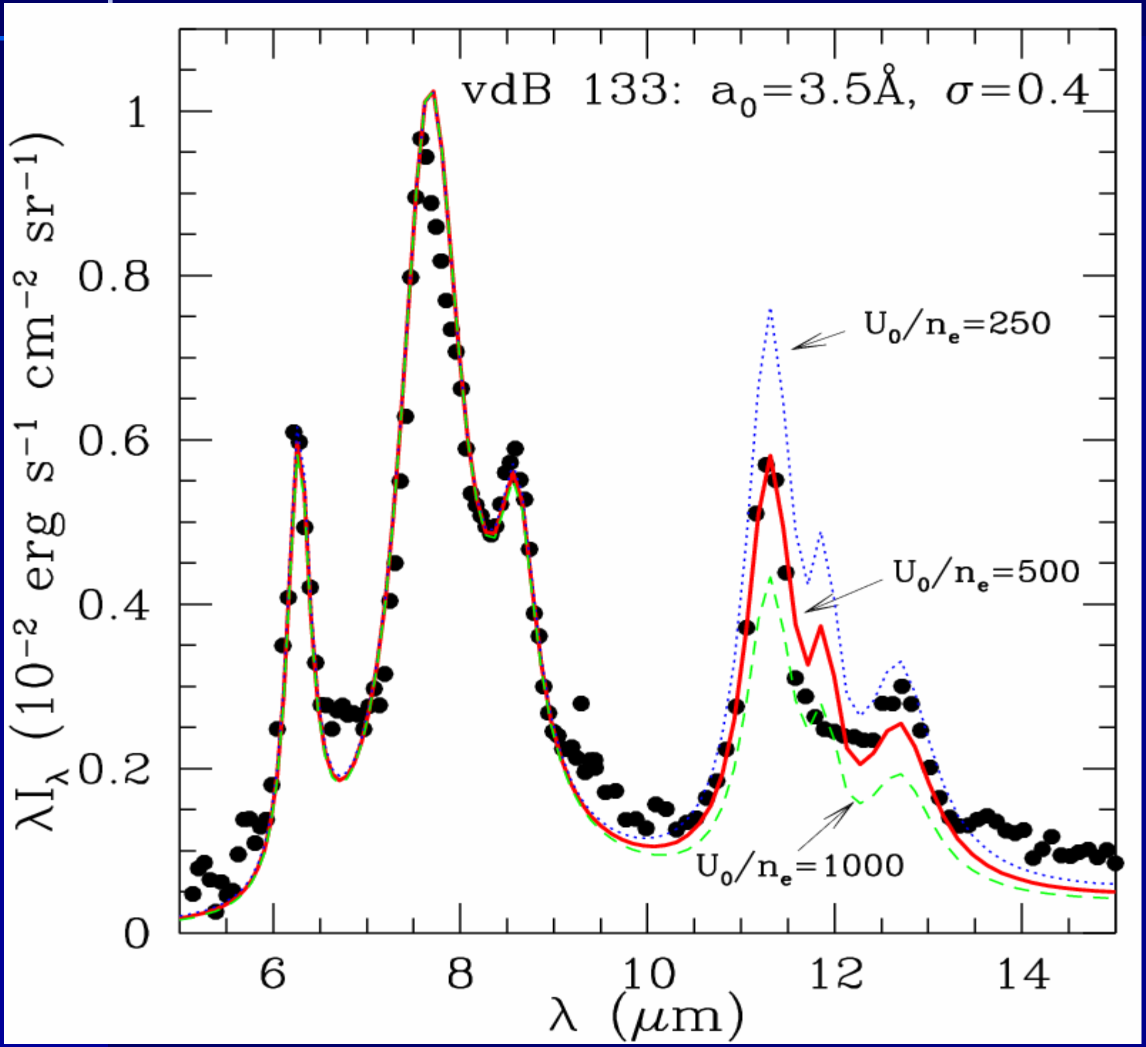
- Vega-type Stars: MS stars with dust disks;
- SAO 206462: F8V, T_eff=6250K (Coulson & Walther 1995);





PAH Excitation

(Li & Draine 2002)



- Cool reflection nebula vdb 133 (T_{eff}=6800K);
- PAHs can be excited by visible/near-IR photons!

Attogram (10^{-18} g) Dust?

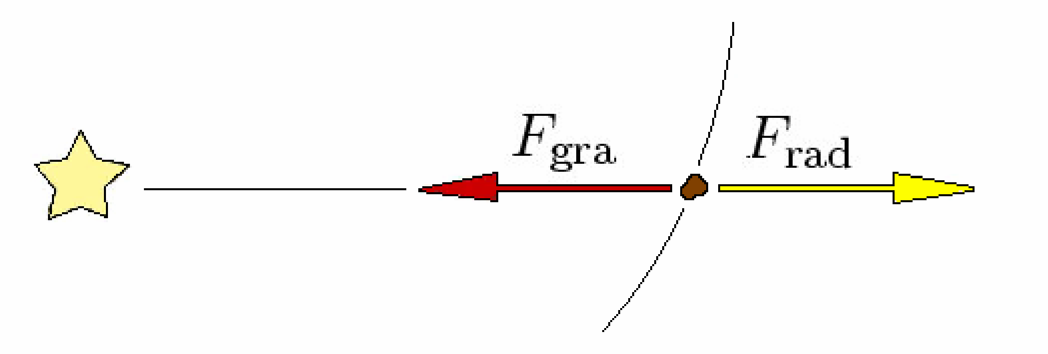
Nanometer sized dust grains do not absorb radiation effectively enough to be pushed out by radiation pressure.

They are heated by single photons to high enough temperatures to emit at the silicate features (e.g. BD+20 307).

They are detected in disks (Forrest et al. 2007)!

See Mann et al. (2006, Planet. Space Sci.) for a review on nano-sized dust in solar system.

Opposing Forces



$$\text{Radiative Expulsion}: \quad F_{\text{rad}} \propto \frac{a^2\, Q_{\text{rad.pr}}\, L_\star}{r^2} \propto \frac{a^2\, Q_{\text{rad.pr}}}{r^2}$$

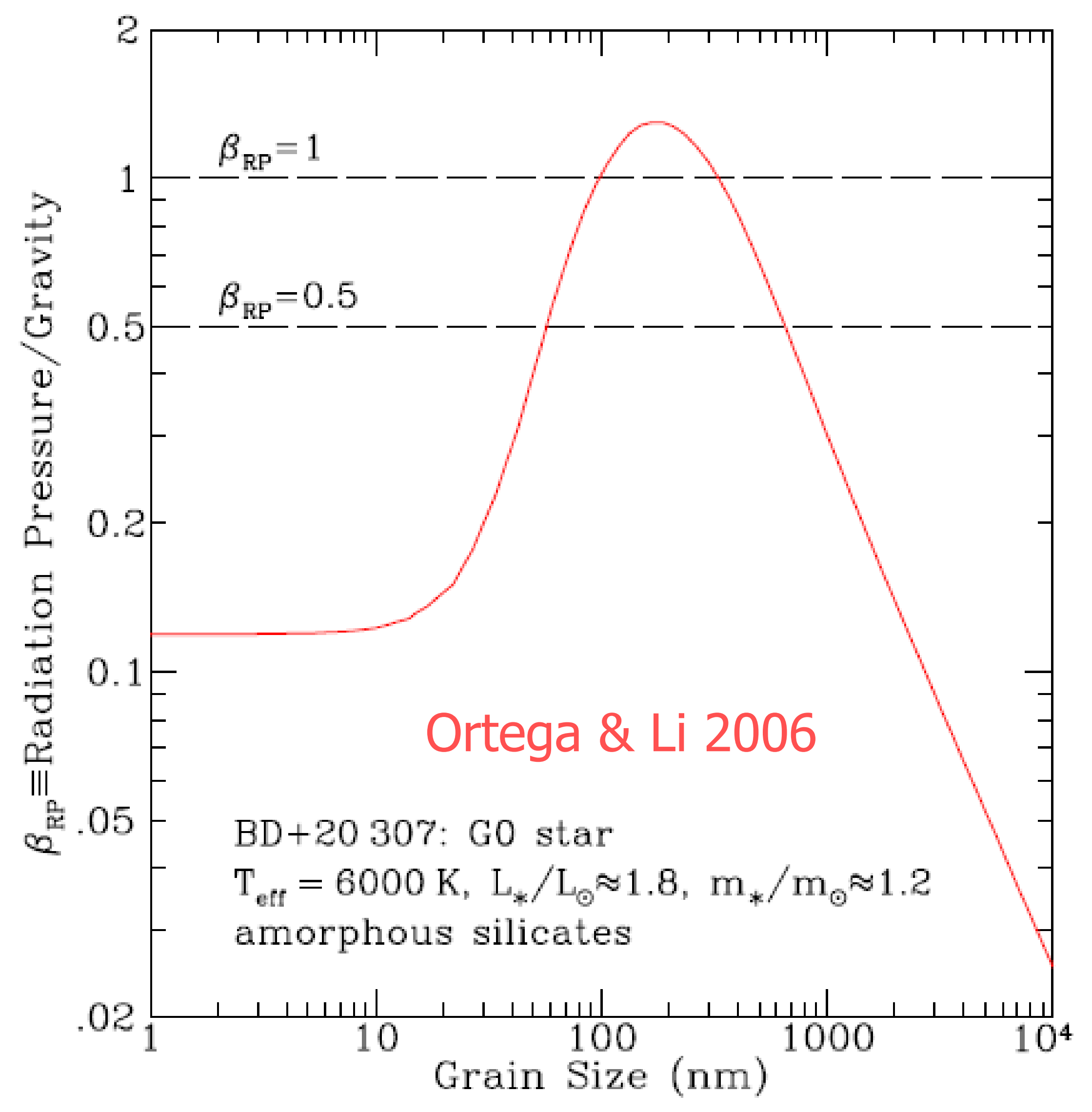
$$\text{Gravitational Attraction}: \quad F_{\text{gra}} = \frac{G\, M_\star\, m_{\text{dust}}}{r^2} \propto \frac{a^3}{r^2}$$

$$\beta_{\text{rp}} \quad \Longrightarrow \frac{F_{\text{rad}}}{F_{\text{gra}}} \propto \frac{Q_{\text{rad.pr}}}{a}$$

$$\text{large grains}(a \gg \lambda) : Q_{\text{rad.pr}} \rightarrow \text{constant} \Longrightarrow \frac{F_{\text{rad}}}{F_{\text{gra}}} \propto \frac{1}{a}$$

$$\text{attogram grains}(a \ll \lambda) : Q_{\text{rad.pr}} \propto a \Longrightarrow \frac{F_{\text{rad}}}{F_{\text{gra}}} \rightarrow \text{constant}$$

Attogram Dust Stays in the Disk!



Ortega & Li 2006

Grains a> 0.3 μm:

pulled into the star by Poynting-Robertson drag, or too cold to emit silicate features;

Grains 0.1<a< 0.3μm:

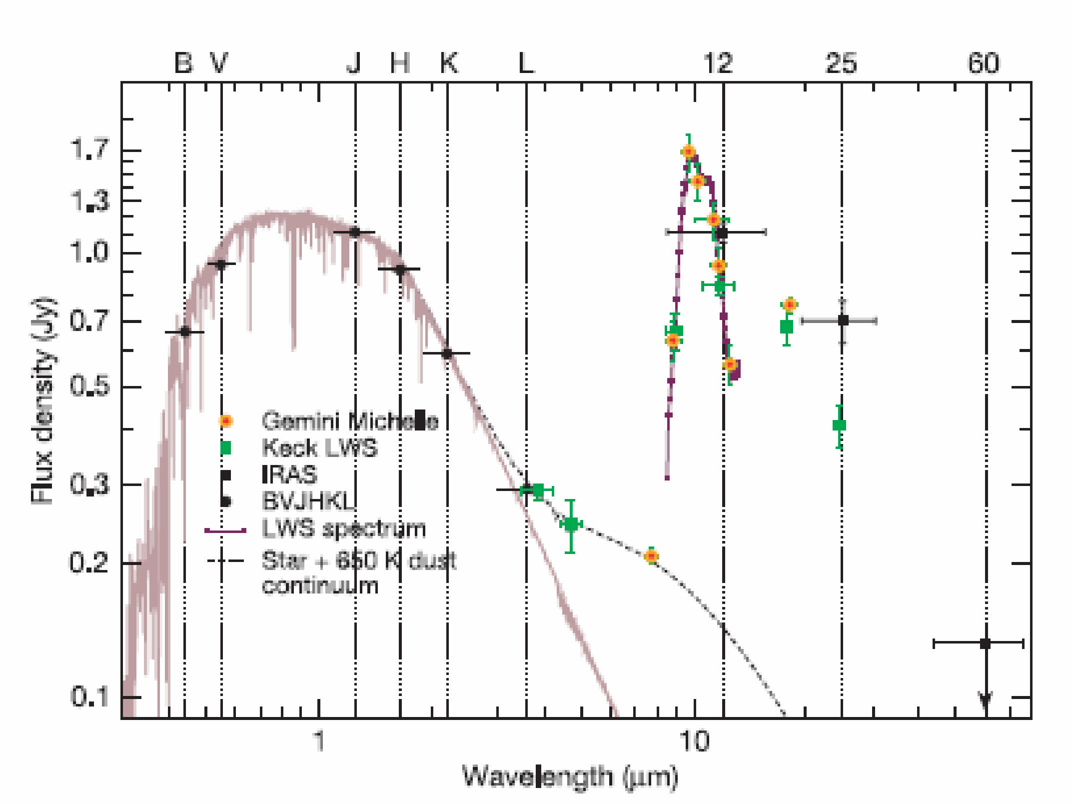
will be pushed out by radiation pressure;

Nanometer sized grains will stay in the disk!

Porous aggregates are easier to be pushed out (Mukai et al. 1992).

BD+20 307

- Using the space motion, lithium content and X-ray flux of the star Song et al. were able to estimate the age of the star at about 300 million years.
- This is more than enough time to have depleted the primordial dust of a few microns in size!



The question is:

How can a star this old show such a silicate feature?

Figure from: Song et al. Nature 436, 363-365 (2005)

Summary

- Debris disks are 2nd generational;
- Debris disks contain important clues for the origin and evolution of exoplanets;
- The porous-dust model is robust!
  - Composition: fluffy aggregates of interstellar-like silicate, carbon, ice dust mixtures;
  - Morphology; porous ($P \sim 0.90$);
  - Size distribution: $dn/da \sim a^{-q}$,

    $a_{min} \leqslant a \leqslant a_{max}$; a_{min}=0.01-1μm, a_{max}=1cm;

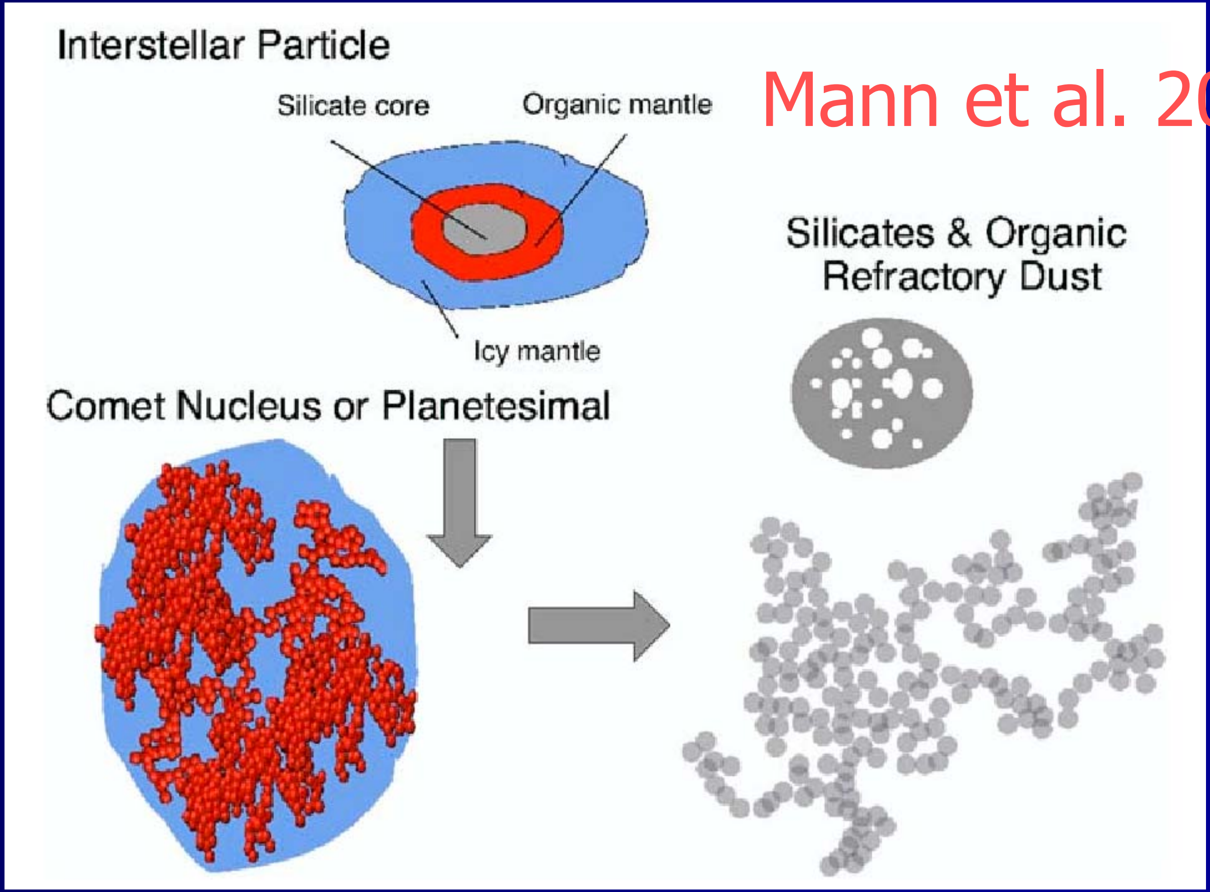
    Dust spatial distributions;

More to Be Done…

- A systematic modeling of debris disks of various masses and ages;
  - with PAHs taken into account;
  - Observational: Spitzer; CanariCam-GCT, LBT, Keck, Gemini, Subaru, VLT; Polarimetric imaging/spectro.;
- SED vs. Disk structure vs. planets;
- Mineralogy: origins of crystalline silicates, PAHs; their possible relations to comets/planetesimals, ISM;
- Extend the Porous dust model to optically-thick gaseous disks/envelopes;
- Ultimate goal ⇨ understand & characterize the origin and evolution of planetary systems!

Part III
(3) Cometary Dust

- Porous aggregate model of cometary dust

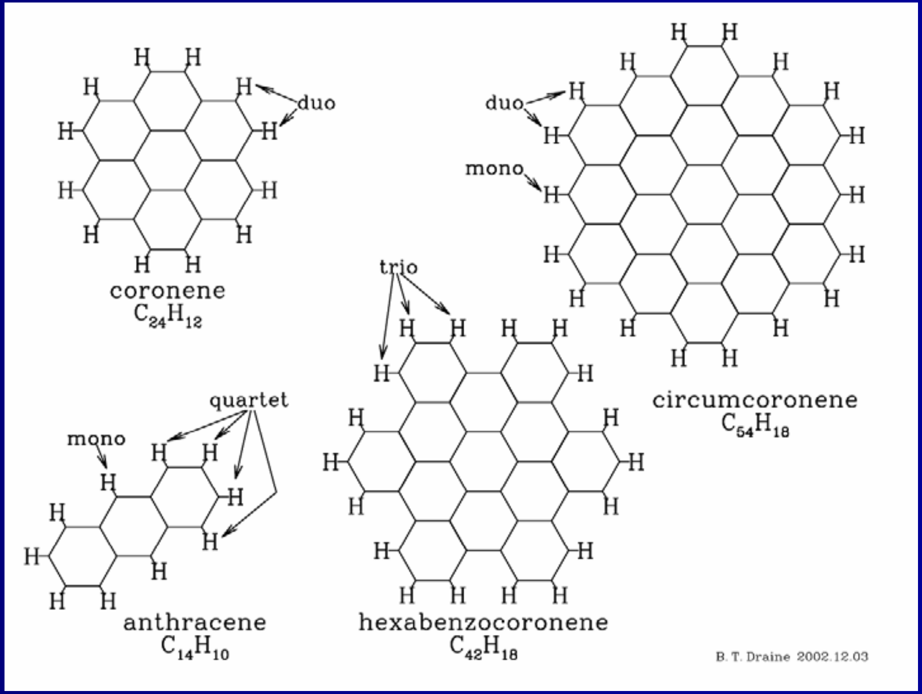


Mann et al. 2006

Porous aggregate model of cometary dust

- Mann et al. 2004, Kimura et al. 2006, Lasue & Levasseur-Regourd 2006: ⇨ successfully reproduces the observed angular and wavelength dependencies of intensity and polarization of scattered solar light by cometary dust.
- D.H. Wooden’s lecture: ⇨ IR emission.

PAHs in Comets?



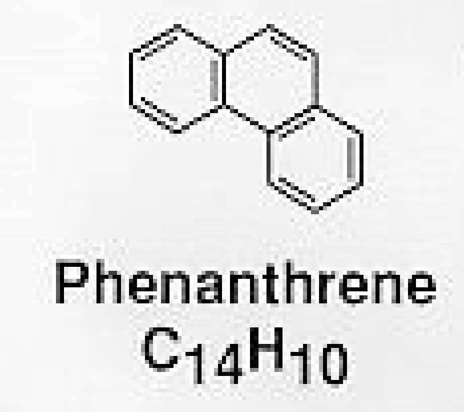
B. T. Draine 2002.12.03

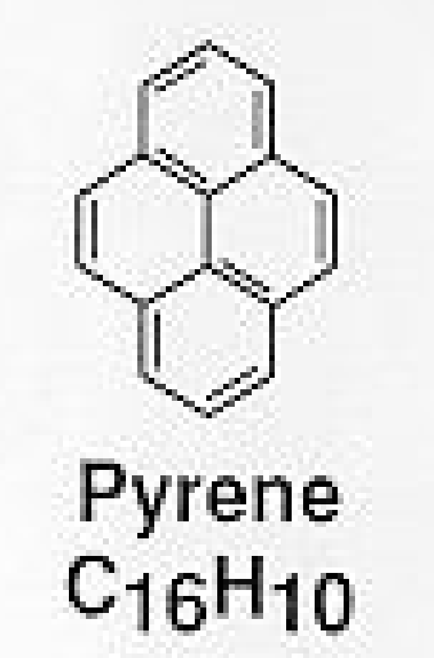
Possible evidence for PAHs in comets:

- mass spectrometry: PAHs in IDPs of cometary origin;
- 3.28μm emission band: PAH C-H stretching mode;
- UV emission spectrum: PAH fluorescence?
- Spitzer IRS spectra of Temple-1: ionized PAHs?

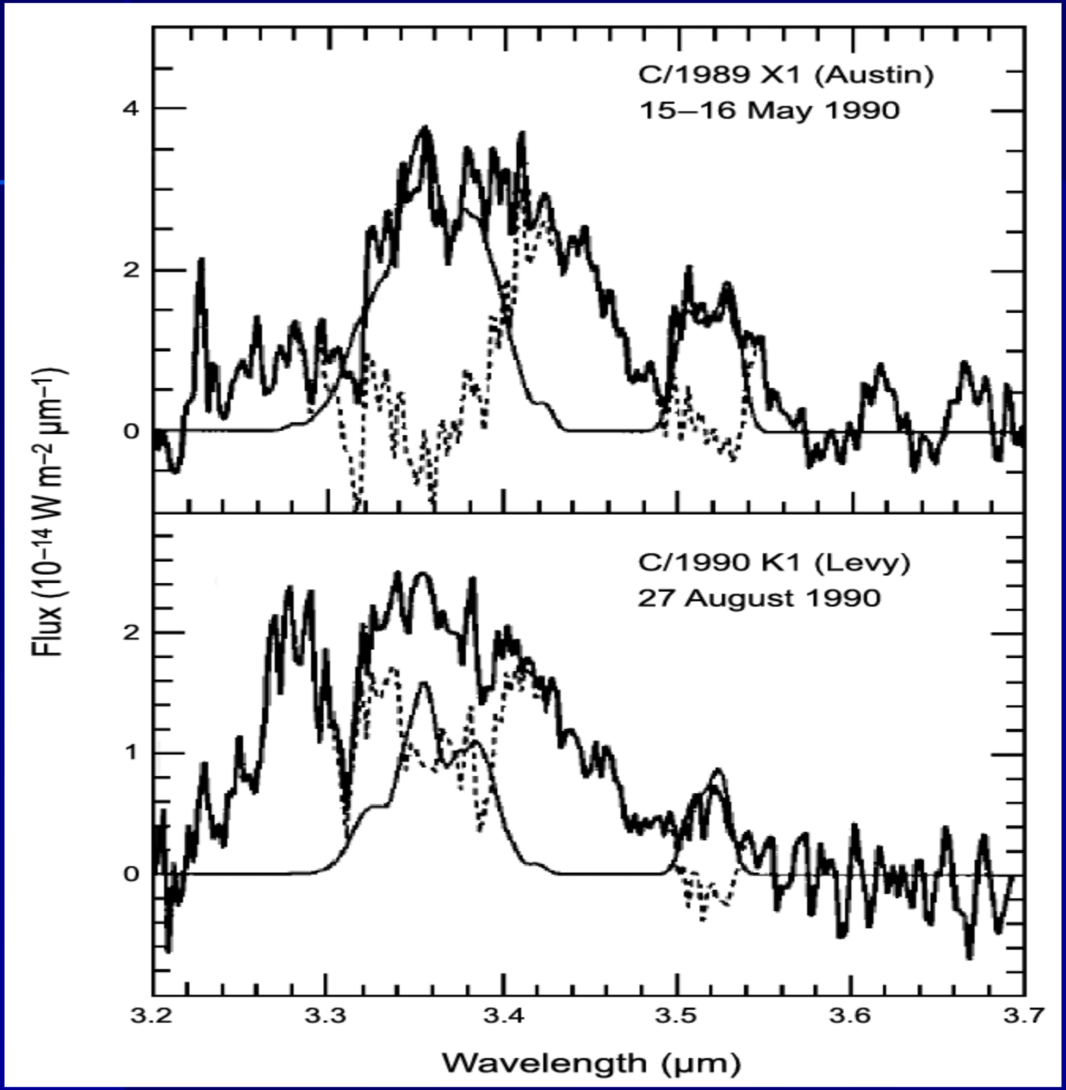
Possible Evidence for PAHs in Comets

- Mass spectrometry: identification of PAHs in interplanetary dust particles (IDPs) of cometary origin (Clemett et al. 1993)
  - ⇨ naphthalene $C_{10}H_8$,
  - ⇨ phenanthrene $C_{14}H_{10}$,
  - ⇨ pyrene $C_{16}H_{10}$;





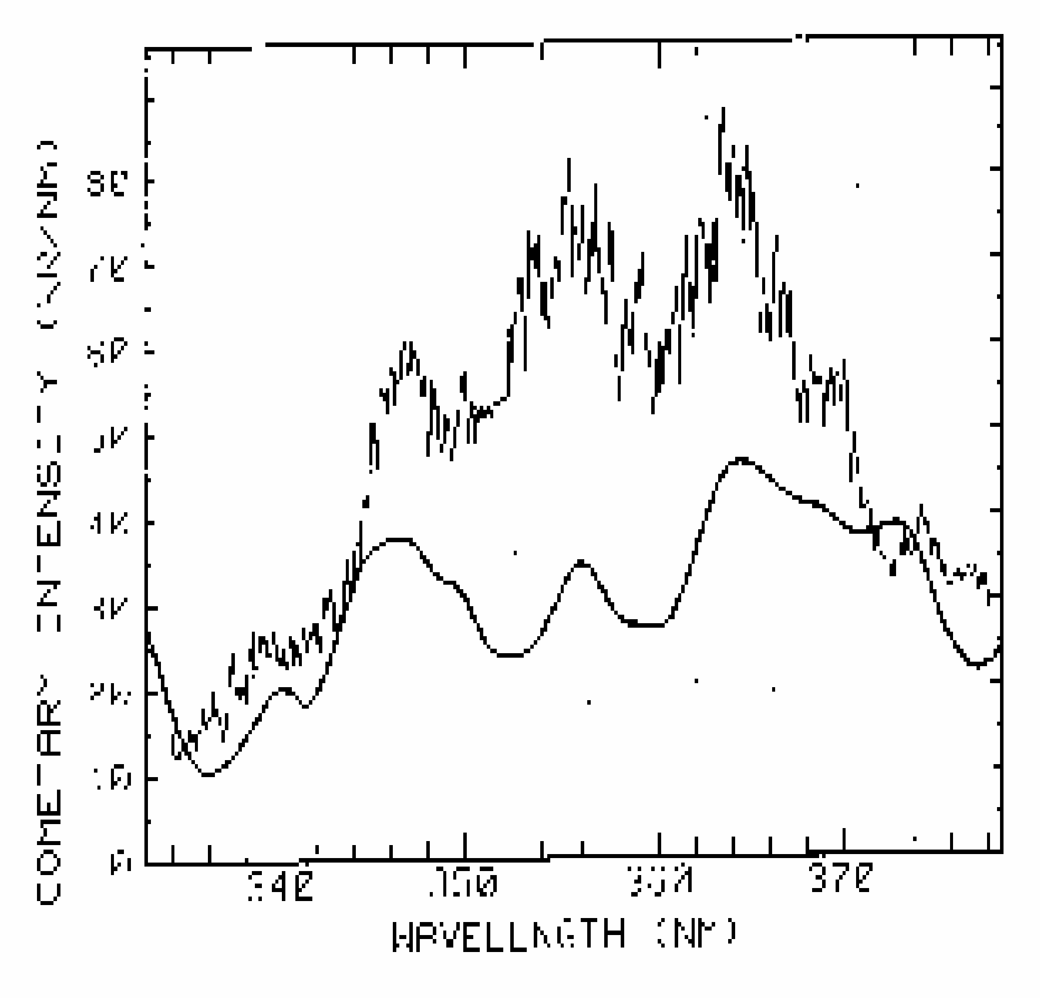
Possible Evidence for PAHs in Comets



- 3.28μm emission band observed in some comets
  - ⇨ PAH C-H stretching mode (Combes 1988, Encrenaz 1988, Bockelee-Morvan et al. 1995);

Bockelee-Movan et al. 1995: PAHs <0.1% of dust prod. Rate

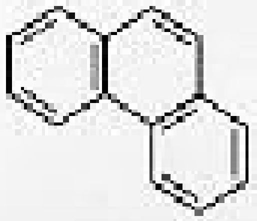
Possible Evidence for PAHs in Comets



- Halley (9 March 1986; r_h=0.83AU): near-ultraviolet fluorescence spectrum

at 347, 356, 375nm

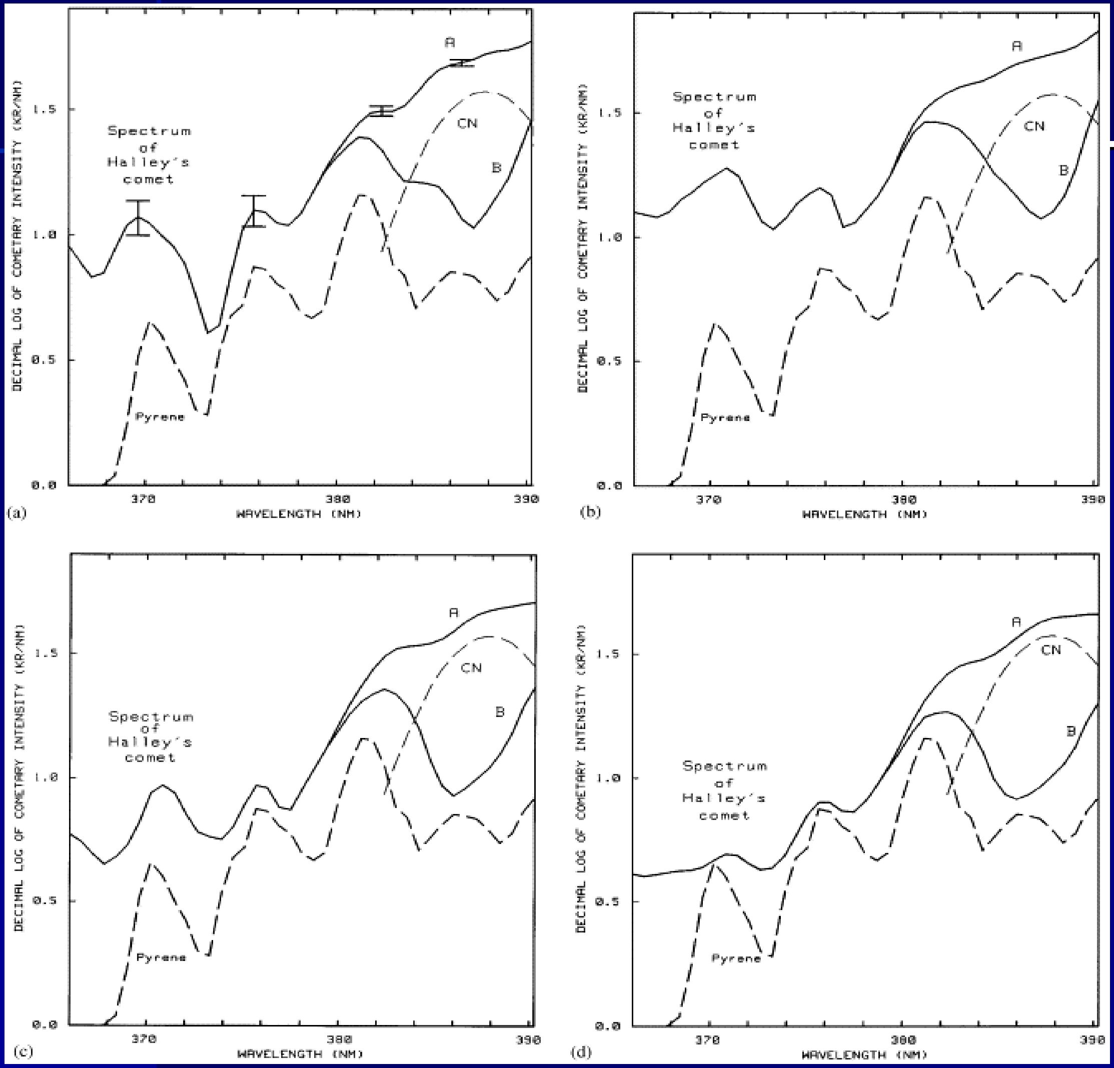
⇨ phenanthrene $C_{14}H_{10}$?



Phenanthrene
$C_{14}H_{10}$

Moreels et al. 1994: ~7% of dust prod. rate

Possible Evidence for PAHs in Comets



- Halley (9 March 1986; r_h=0.83AU): near-UV fluorescence spectrum

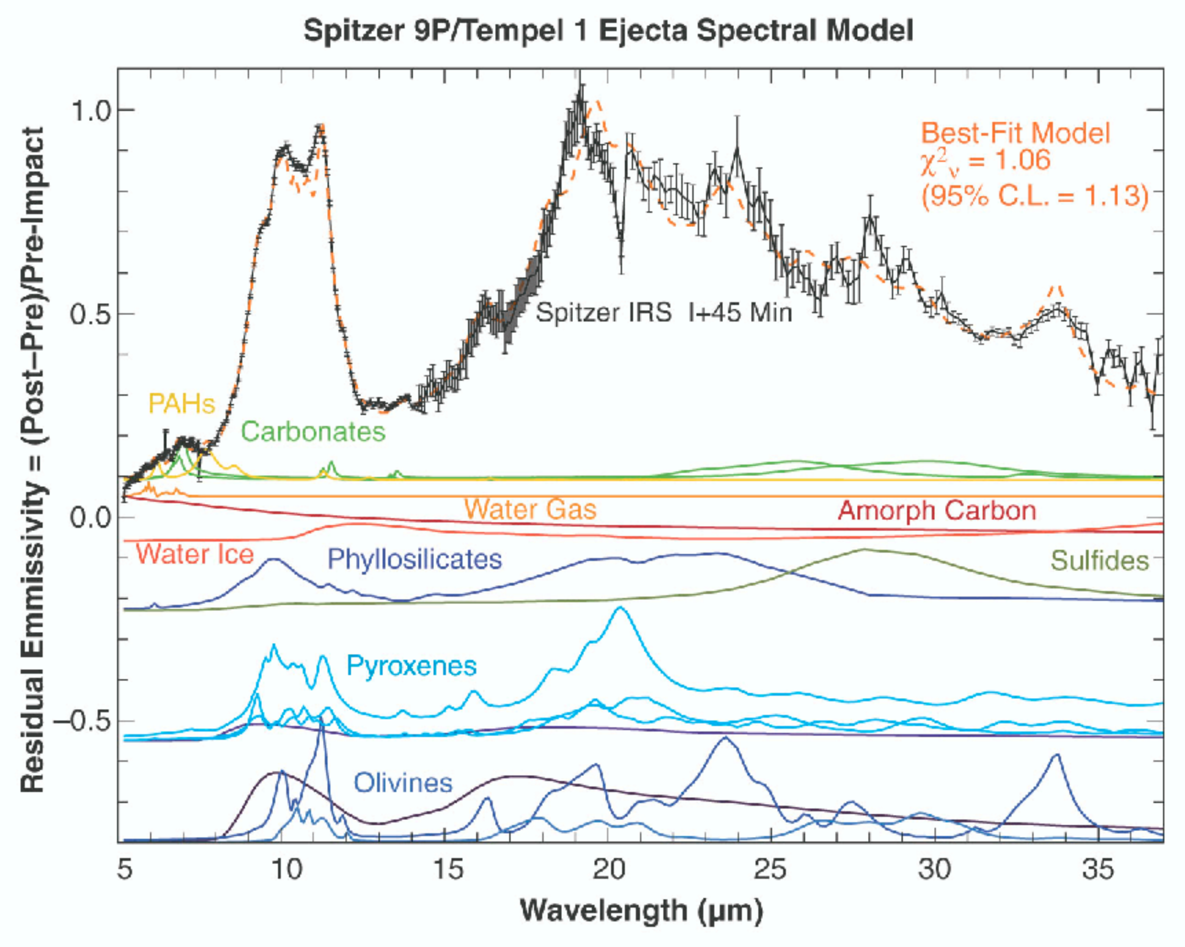
at 371, 376, 382nm

⇨ pyrene $C_{16}H_{10}$?

Clairemidi et al. 2004: ~5.9E25 mol/s

PAHs in Tempel-1 Ejecta?

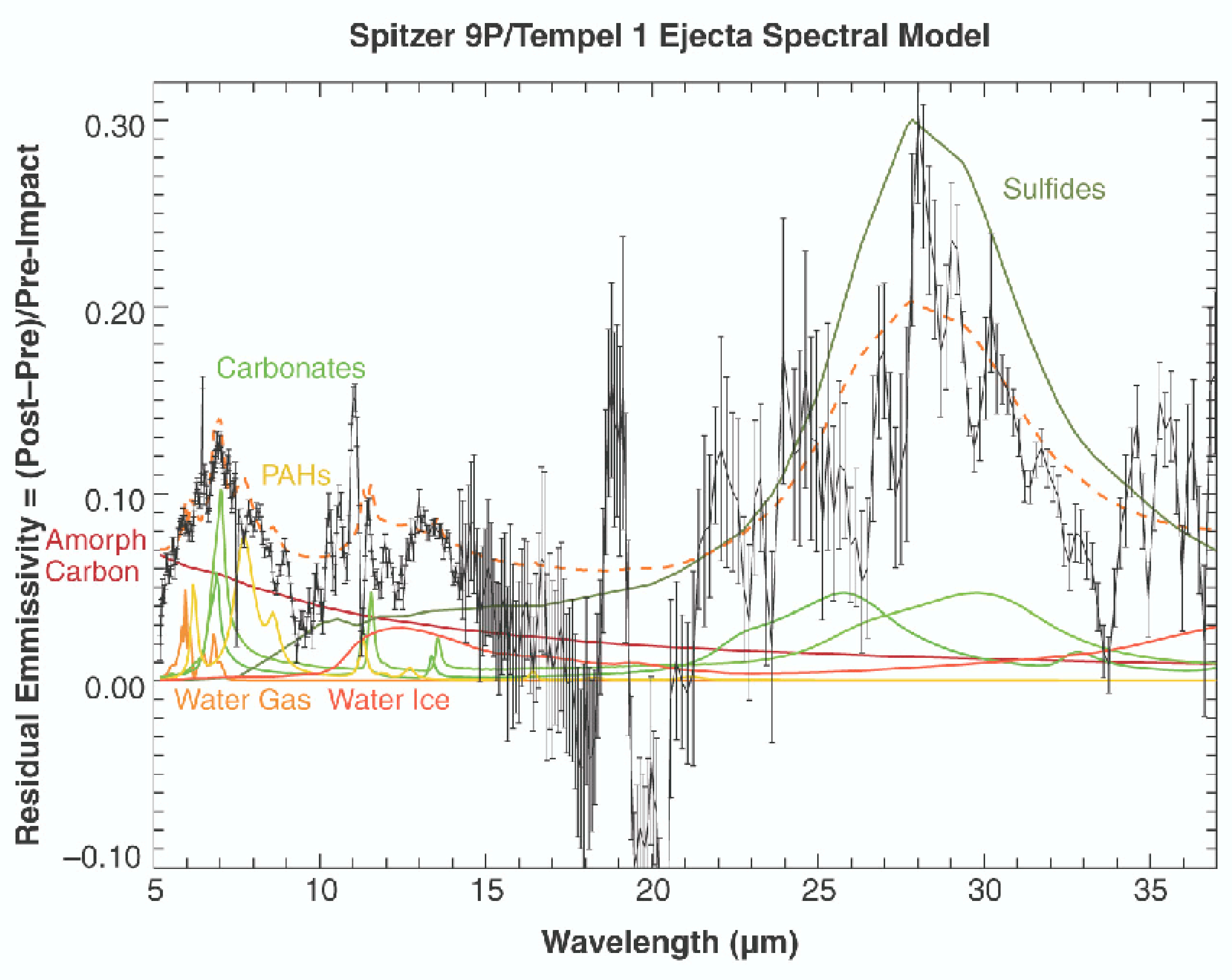
(Lisse et al. 2006, Science)



Lisse: 6.2, 7.7, 8.6μm bands, Harker: weaker or no 11μm band → ionized PAHs?

PAHs in Tempel-1 Ejecta?

(Lisse et al. 2006, Science)



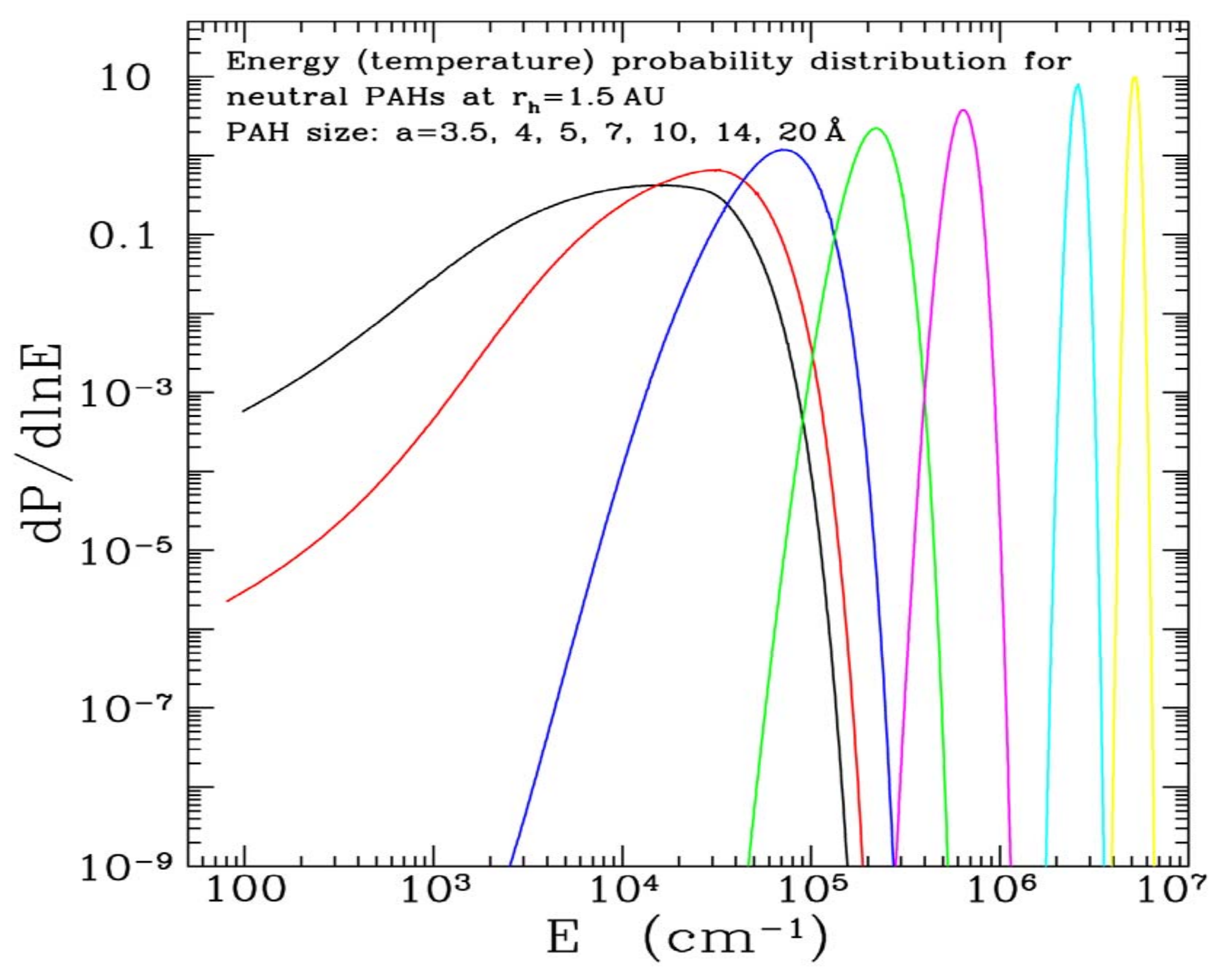
6.2, 7.7, 8.6μm bands, weaker 11μm band → ionized PAHs?

PAHs Seen in Stardust Sample!

Science
December 15th Stardust Special issue

Stochastic Heating of PAHs by Single Solar Photons

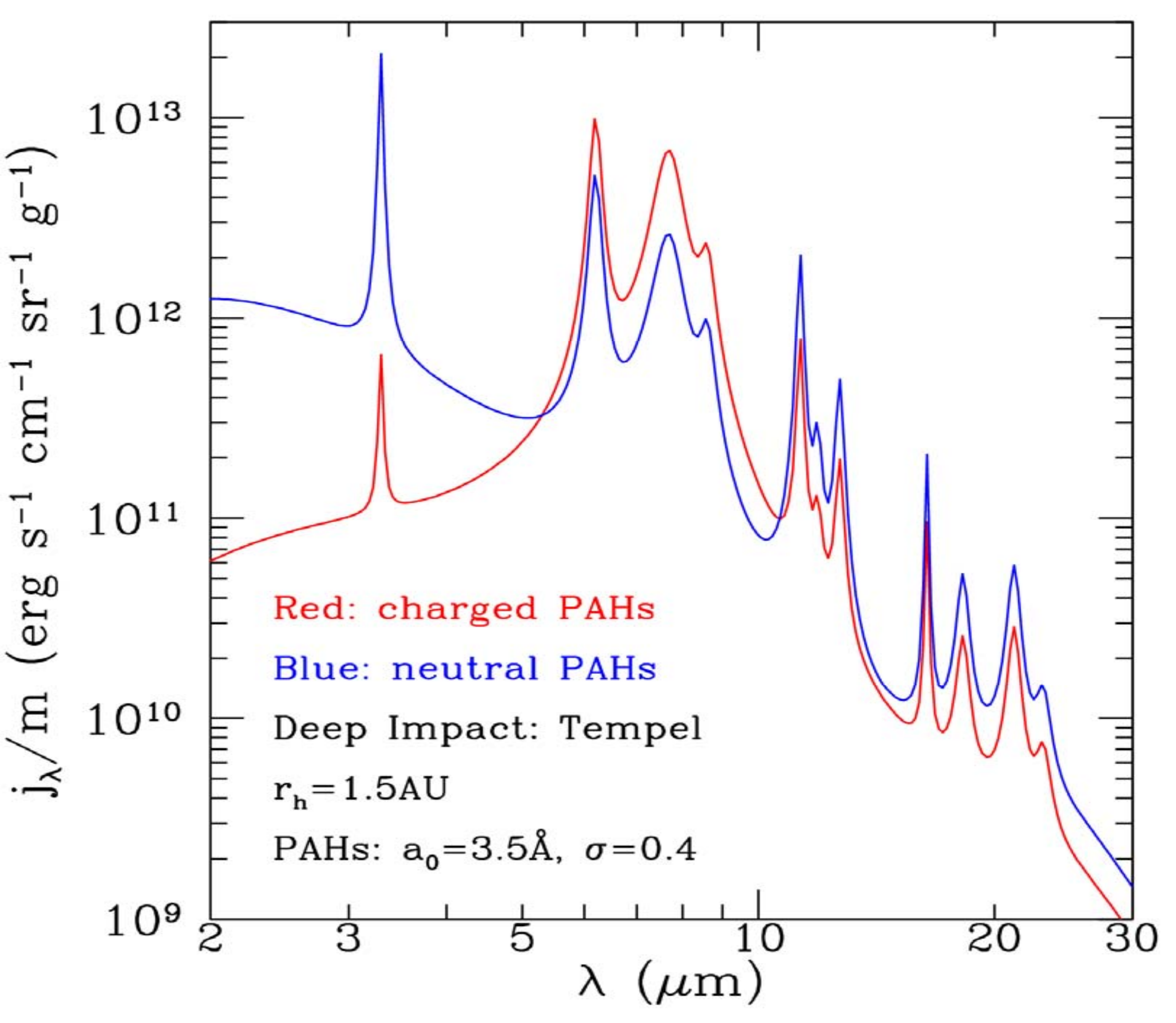
(Li & Draine 2007)



PAHs at r_h=1.5AU

Theoretical IR Emission spectra for PAHs at 1.5 AU Heated by Solar Photons

(Li & Draine 2007)



PAHs at r_h=1.5AU