Interstellar Dust and PAHs

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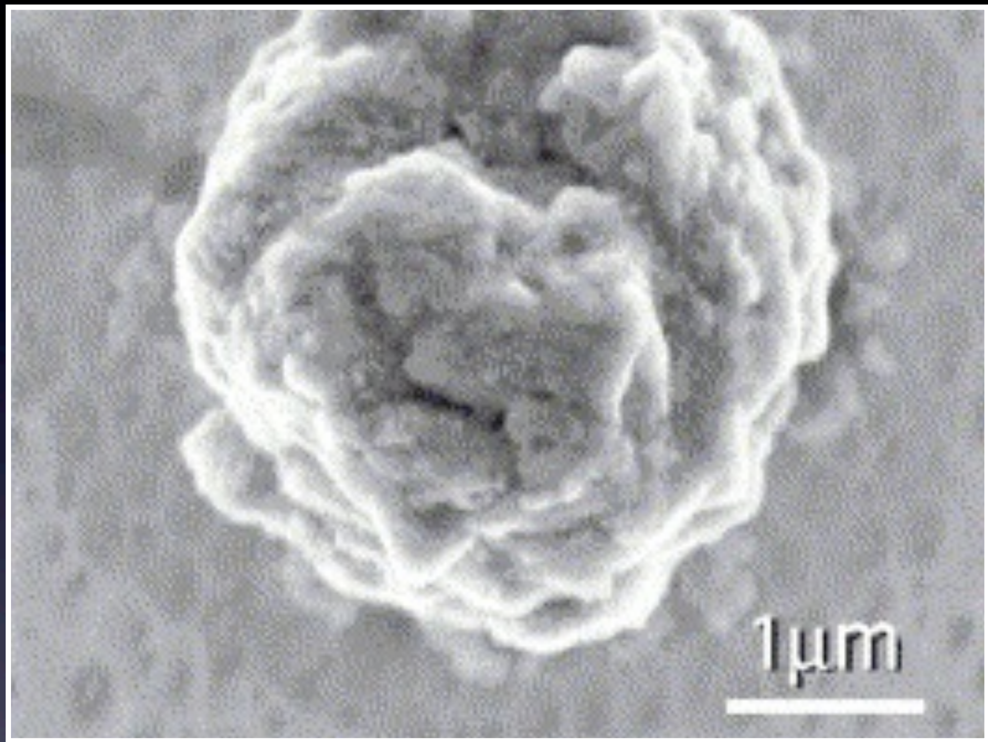
Interstellar Dust

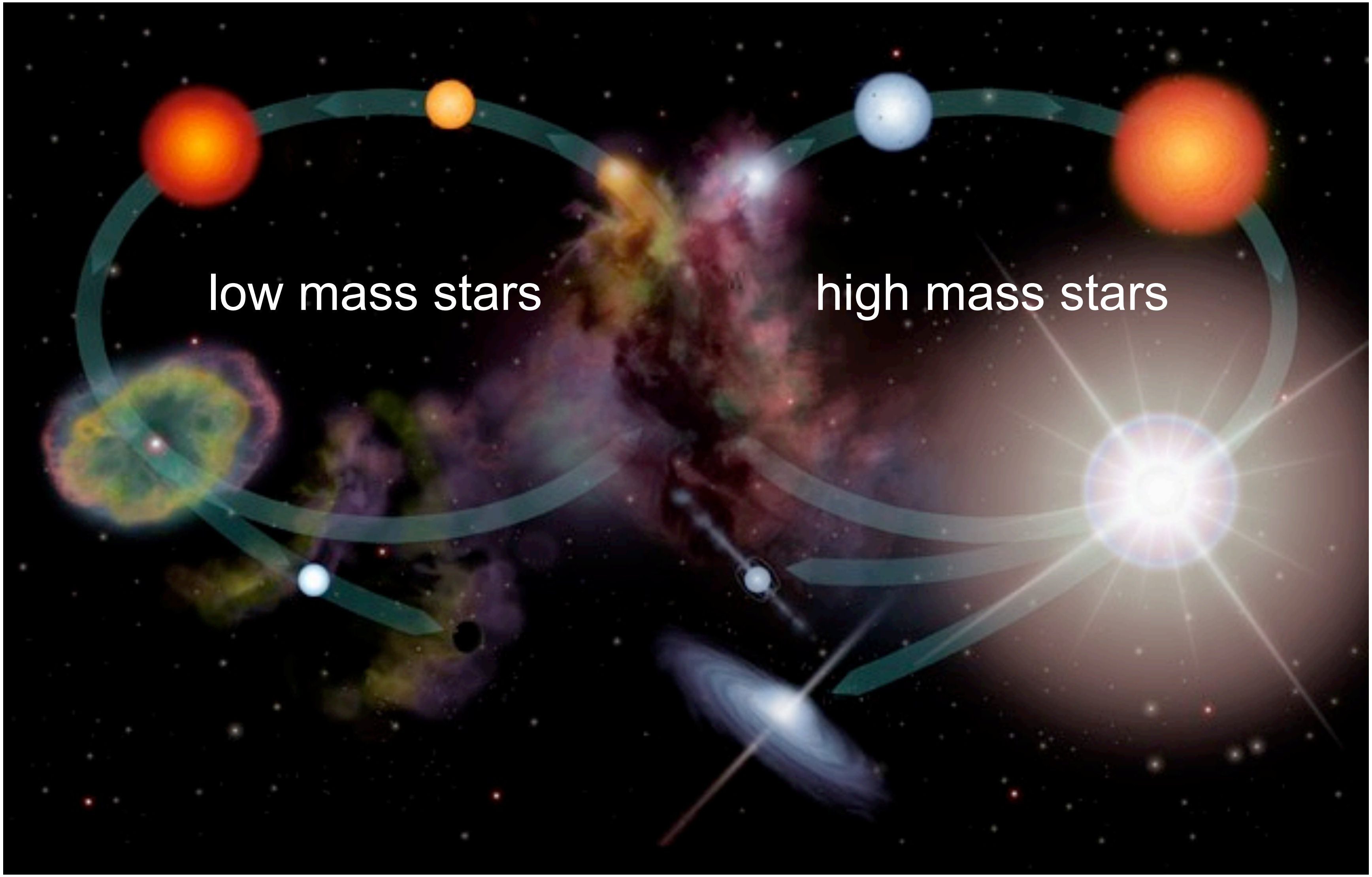
Role of dust:

- Dominant opacity source FUV-submm
- Dominates spectral appearance of galaxies
- Reservoir of elements
- Dust & molecules
    - Limits molecular photodissociation
    - Catalytic surfaces
    - Cold storage
- Photo-electric heating and the energy balance of the gas
- Cosmic Rays
- Building blocks of planetary systems

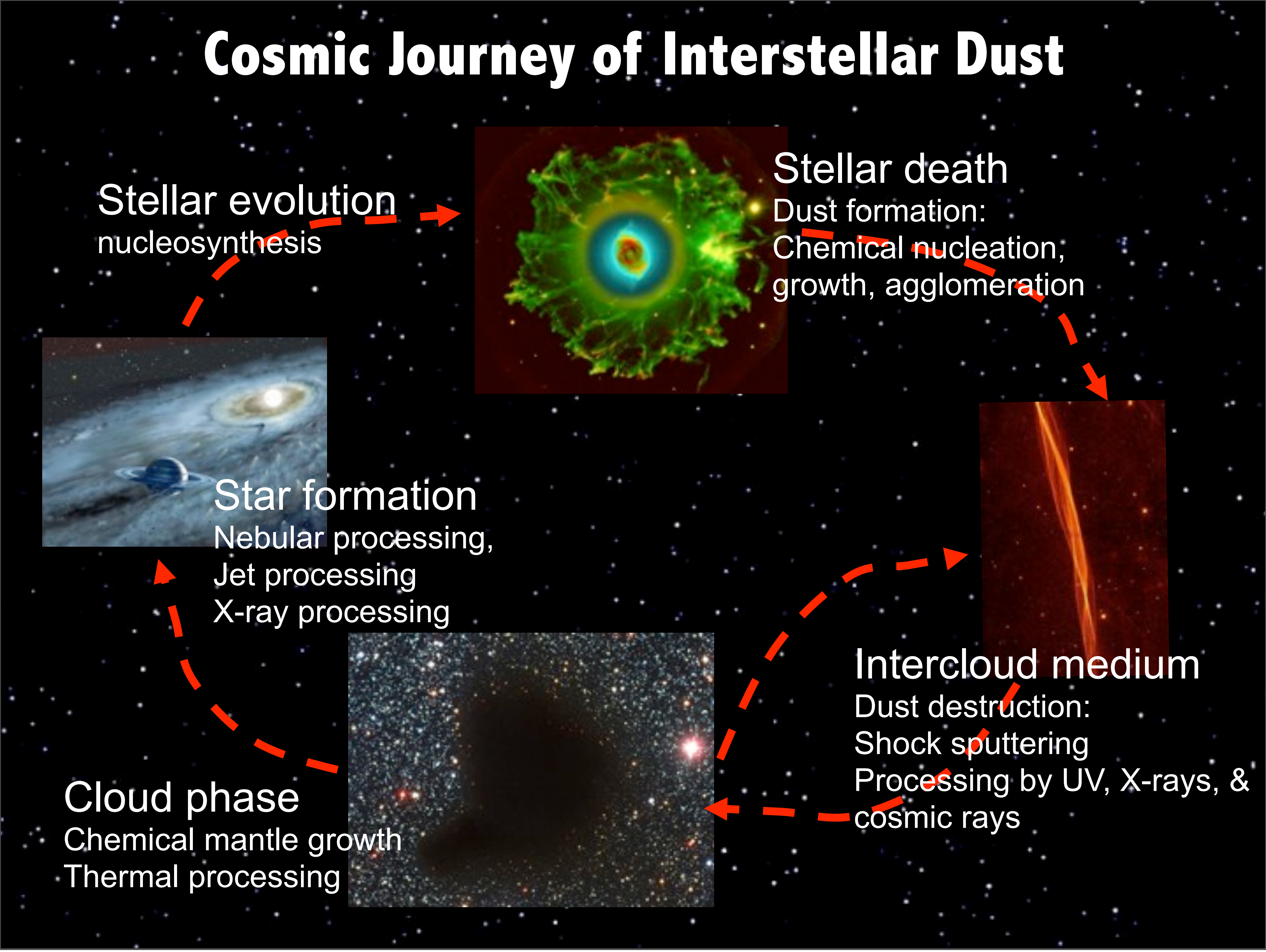


Tielens Ancestry

The Lifecycle of Baryonic Matter



credit: http://hea-www.cfa.harvard.edu/CHAMP/EDUCATION/PUBLIC/ICONS/


Cosmic Journey of Interstellar Dust
Stellar evolution
nucleosynthesis
Stellar death
Dust formation:
Chemical nucleation,
growth, agglomeration
Star formation
Nebular processing,
Jet processing
X-ray processing
Intercloud medium
Dust destruction:
Shock sputtering
Processing by UV, X-rays, &
cosmic rays
Cloud phase
Chemical mantle growth
Thermal processing

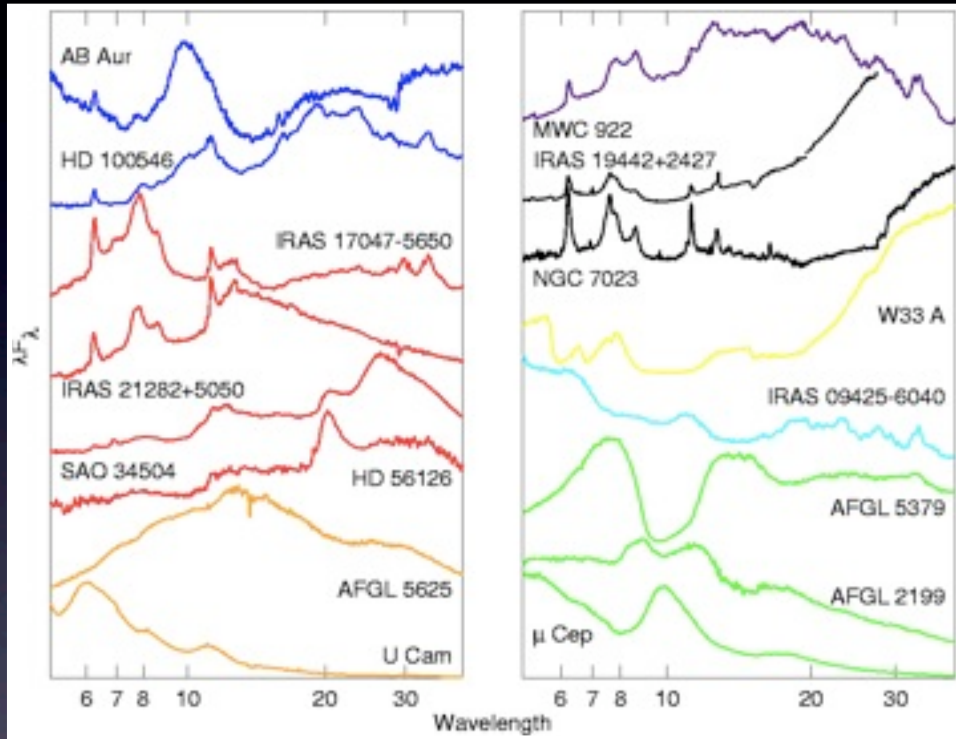
Key Questions

- What is the inventory of interstellar dust ?
- What are the important sources of dust and how does that depend on metallicity and star formation rate of the galaxy ?
- What processes played a role in the evolution of dust in the interstellar medium ?
- What kind of dust entered the Solar Nebula ?
- What processes played a role in the evolution of dust in the planetary systems ?
- How did dust evolve with time in the Universe ?
- How is dust affected near black holes and in starburst environments ?
- How did the evolution of dust affect the evolution of galaxies, stars and planets ?

Probing the Dust:
1 Dust Inventory

The Spectral Richness of Dust

- ISO and Spitzer have revealed the incredible spectral richness of interstellar dust
- JWST will carry this to the era of vigorous star formation in the Universe
- SPICA will probe the high-z Universe
- Herschel will probe the far-IR
- SOFIA can probe bright stardust sources in the Milky Way to link these spectral characteristics to the characteristics of the stardust sources and turn this into a tool for understanding the origin of dust in the Universe



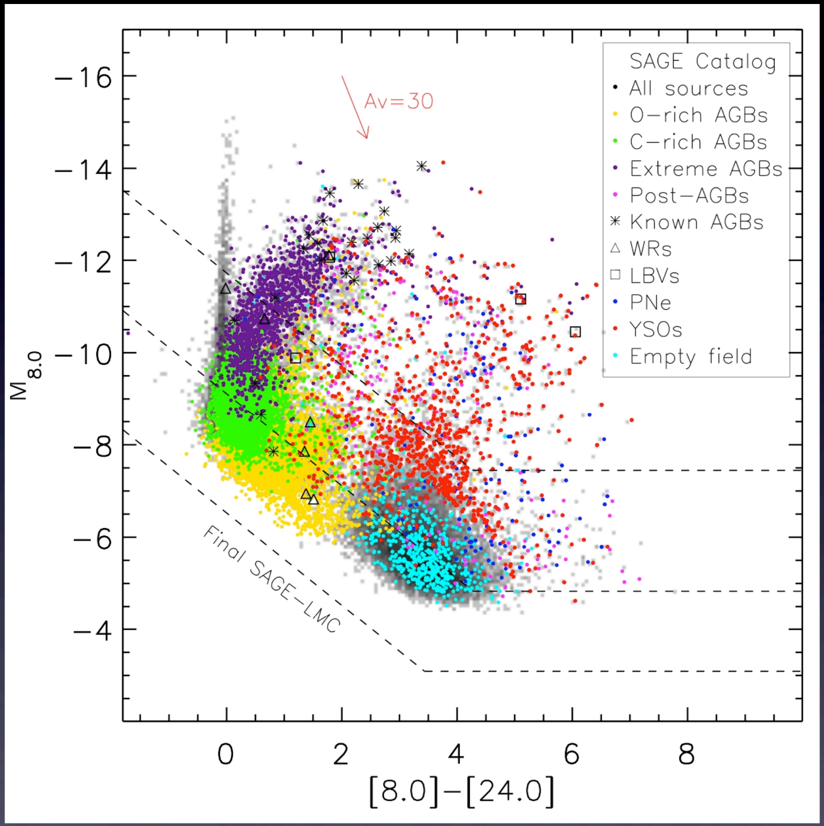
Hony, 2001, PhD thesis

Dust Inventory of the ISM

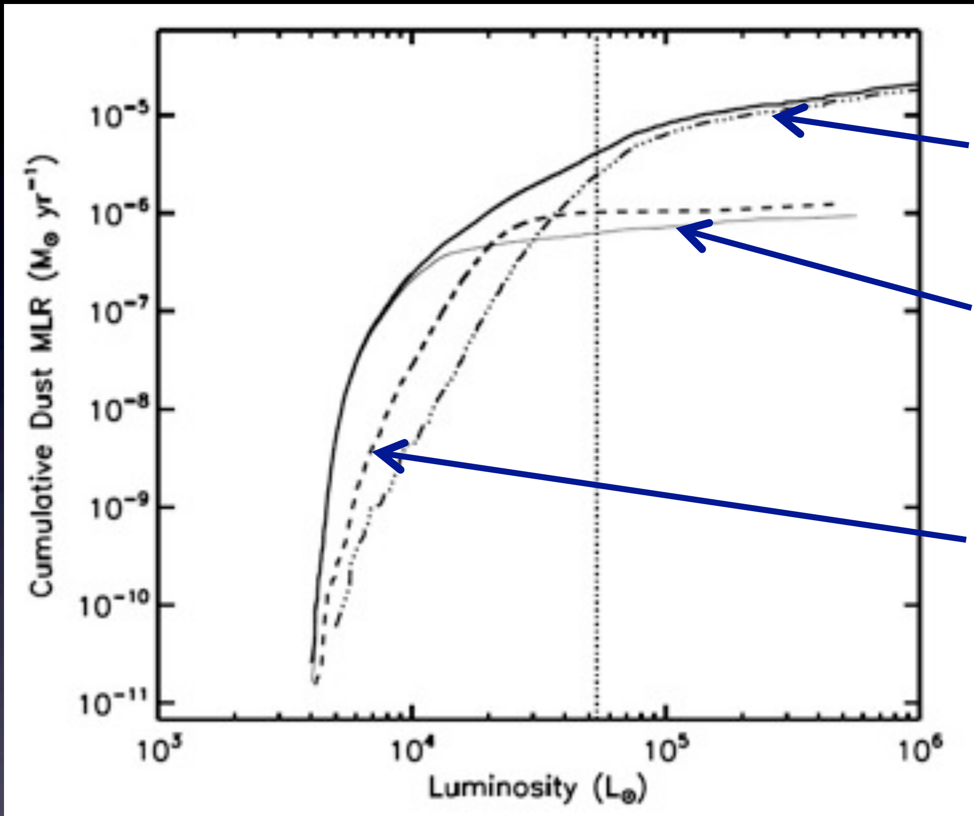
- Silicates:
  - Amorphous FeMg-silicates
  - Forsterite
  - Enstatite
  - Montmorillonite ?
- Oxides:
  - Corundum
  - Spinel
  - Wuestite
  - Hibonite
  - Rutile
  - Silica
- "Pure" Carbonaceous compounds:
  - Graphite
  - Diamonds
  - Hydrogenated Amorphous Carbon
  - Polycyclic Aromatic Hydrocarbons
- Carbides:
  - Silicon carbide
  - Titanium carbide
  - And others
- Sulfides:
  - Magnesium sulfide
  - Iron sulfide ?
- Ices
  - Sinple molecules such as H_2O, CH_3OH, CO, CO_2
- Others:
  - Silicon nitride
  - Metalic iron ??
  - Carbonates ?
  - Silicon ??

Sources of Stardust

- Spitzer: Origin of dust in the low metallicity Magellanic Clouds (SAGE & SAGE-Spec)



AGB Stars & the ISM in the LMC



Extreme AGB ~$2.4x10^{-5}$ M_o/yr

O-rich AGB ~$1.4x10^{-6}$ M_o/yr

C-rich AGB ~$2.4x10^{-6}$ M_o/yr

Srinivasan et al, 2009, AJ, 137, 4810

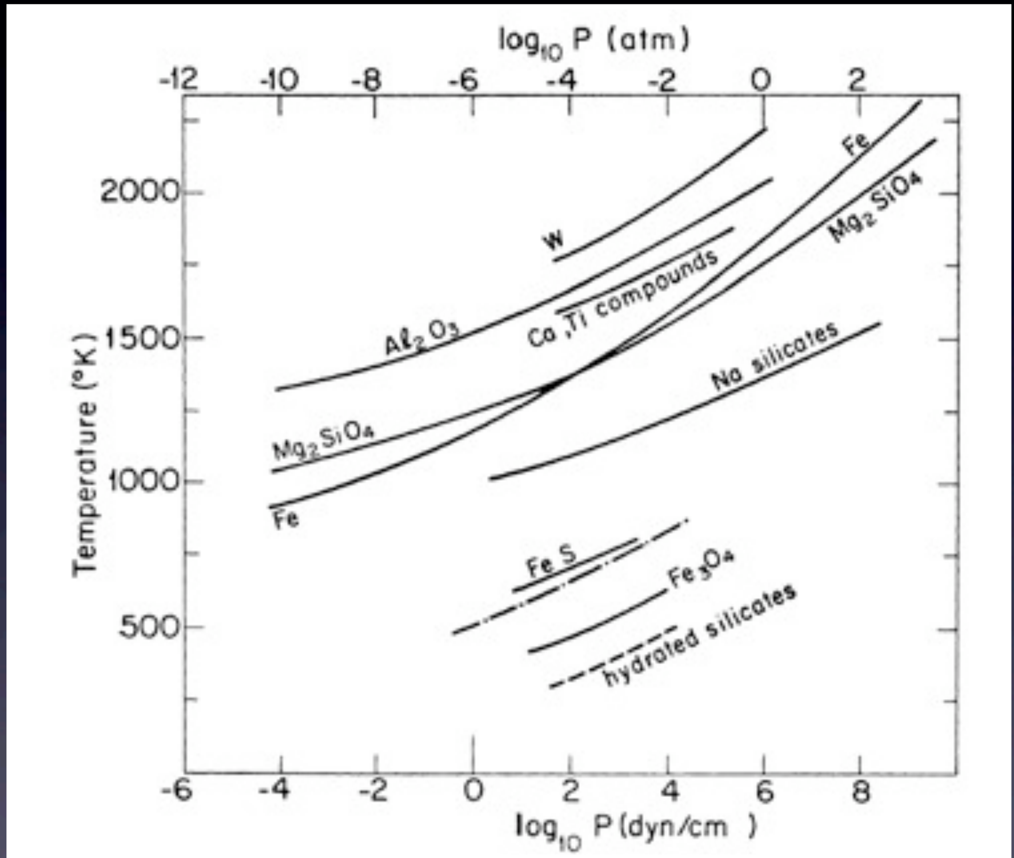
Dust mass injection into the ISM:
~23,000 AGB stars & $2.7x10^{-5}$ M_o/yr

- SOFIA can provide a full census of stardust injected into the Milky Way and compare it to interstellar dust characteristics
- JWST can uniquely probe punctuated evolution: contributions from e.g., captured dwarf galaxies
- JWST can probe IR dust extinction
- Volume limited sample of stardust sources in the Milky Way based on GAIA (2012-2020) distances

Cosmic Journey of Dust:
2 Dust Formation

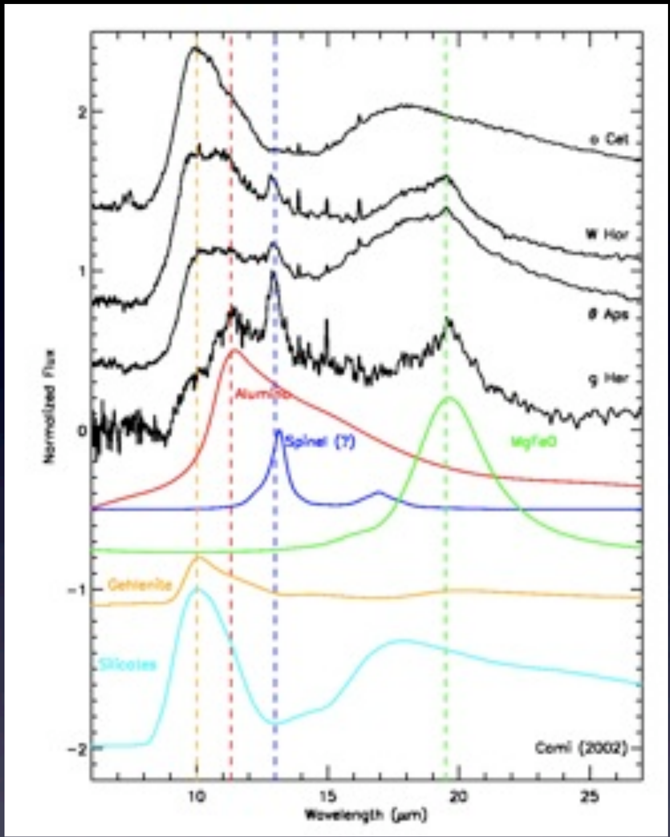
Thermodynamic Condensation Sequence

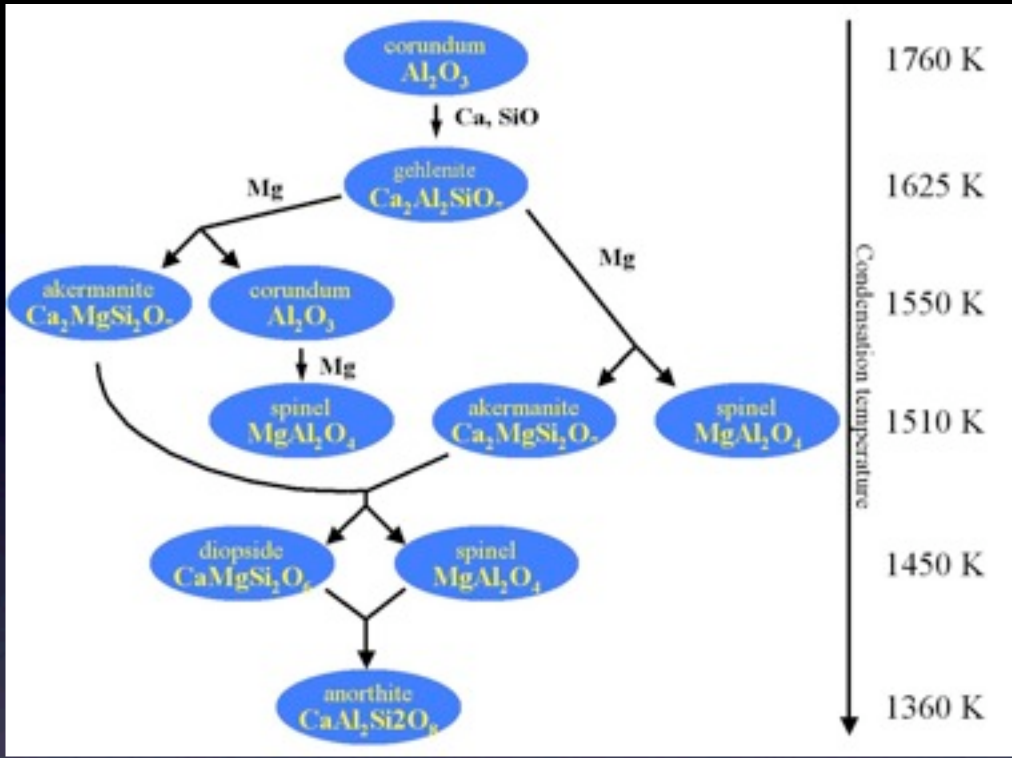
- Gas with solar system composition
- Condensation is sequential
- Two major sequences
  - Oxides: starting with aluminum oxide/spinel and ending with Ca,Al silicates
  - Silicates: starting with forsterite and forming enstatite
- Separate sequence for C-rich gas characterized by carbonaceous compounds



Salpeter, 1977, ARAA, 15, 267

Oxides Condensation Sequence





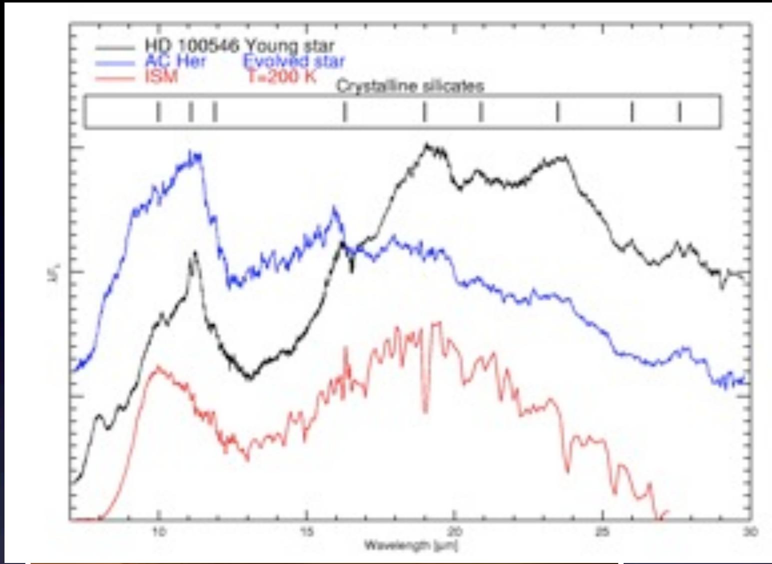
- Oxides at low mass loss rates
- Freeze out

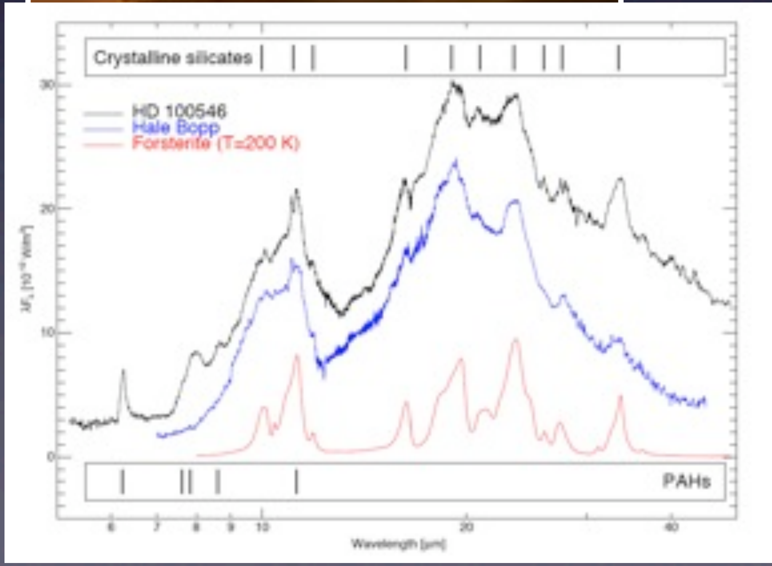
Refs: Cami, 2001, PhD thesis; Posch et al., 2002, A&A, 393, L7; DePew et al., 2006, ApJ, 640, 97; Sloan & Price, 1998, ApJS, 119, 1411

The Incredibly Rich mid-IR Spectrum of Crystalline Silicates

Characteristics

- Crystalline silicates
  - Forsterite/enstatite
  - Magnesium-rich
  - Cold
  - Disk sources
- Amorphous silicates
  - Role of iron
- High mass loss rates
- The silicate condensation sequence





Refs: Malfait et al. 1998, A&A 332, L25; Molster et al., 2000, A&A 382, 184; Kemper et al, 2004, ApJ 609, 826; Crovisier et al, 1997, Science, 275, 1904; Watson et al., 2009, ApJS, 180, 84; Sicilia-Aguilar et al., 2007, ApJ, 659, 1637

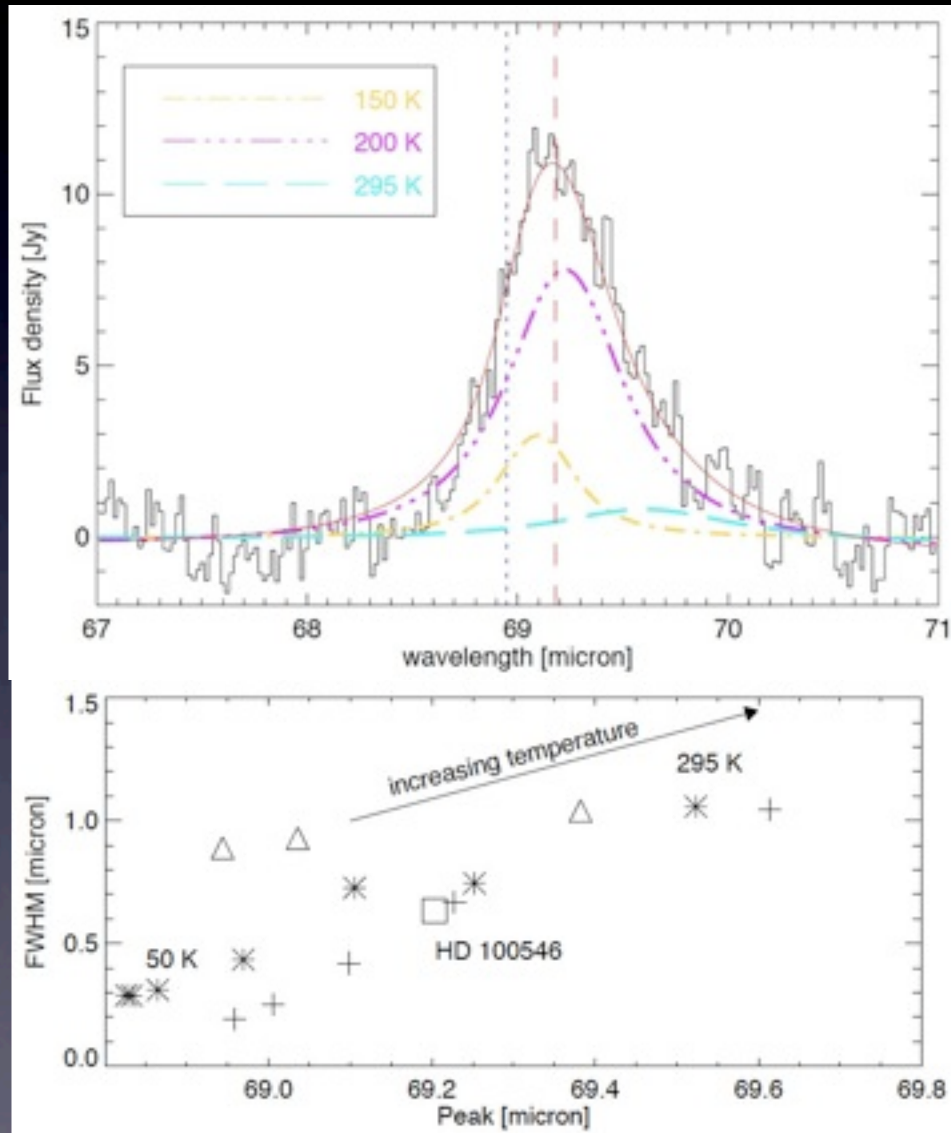
The 69 μm band

Crystalline band characteristics:

Peak position and width depend on the composition and temperature of the material

Mg-rich end members of the olivine and pyroxene families (Fe/Mg<5%): Forsterite and enstatite

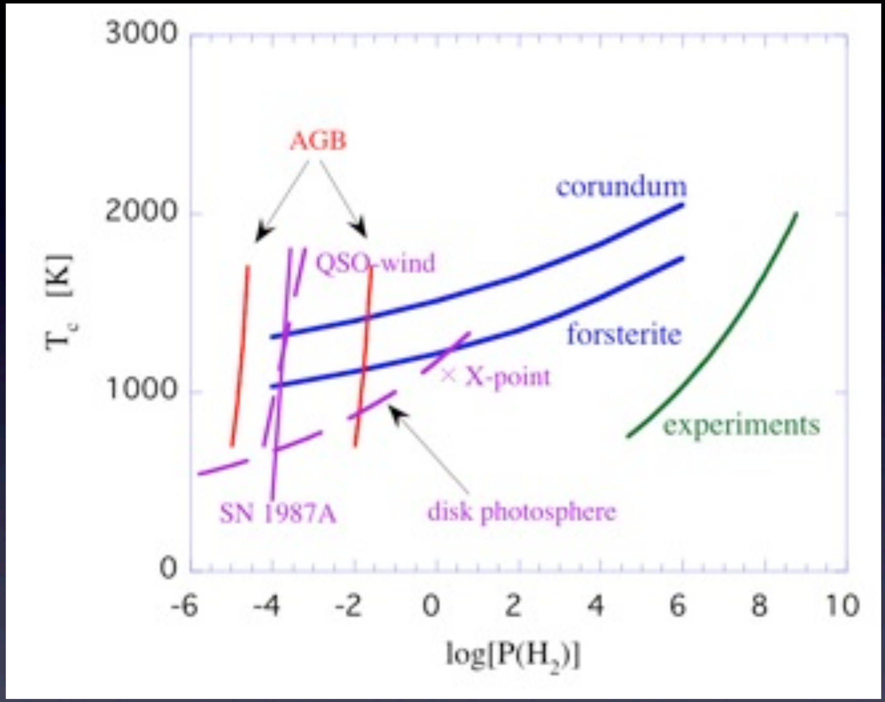
T~100-200K



Refs: Koike et al, 2000, AA, 363, 1115; Molster et al, 2002, AA, 382; Bowey, 2002, MNRAS, 331, L1; Sturm et al, 2010, astroph

AGBs as Dust Condensation Laboratory

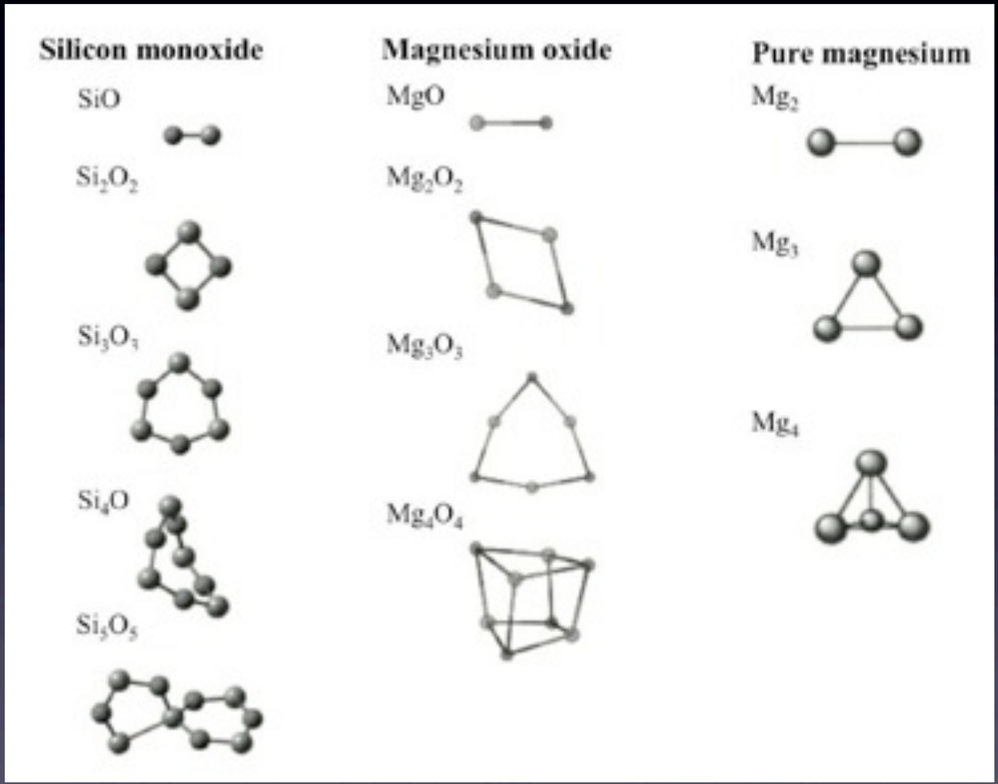
- Two condensation sequences:
  - Oxides
  - Silicates
- Time is of the essence
- AGBs are templates for SNe and other dust factories
- Controlled stellar samples are required



Tielens, 2010,

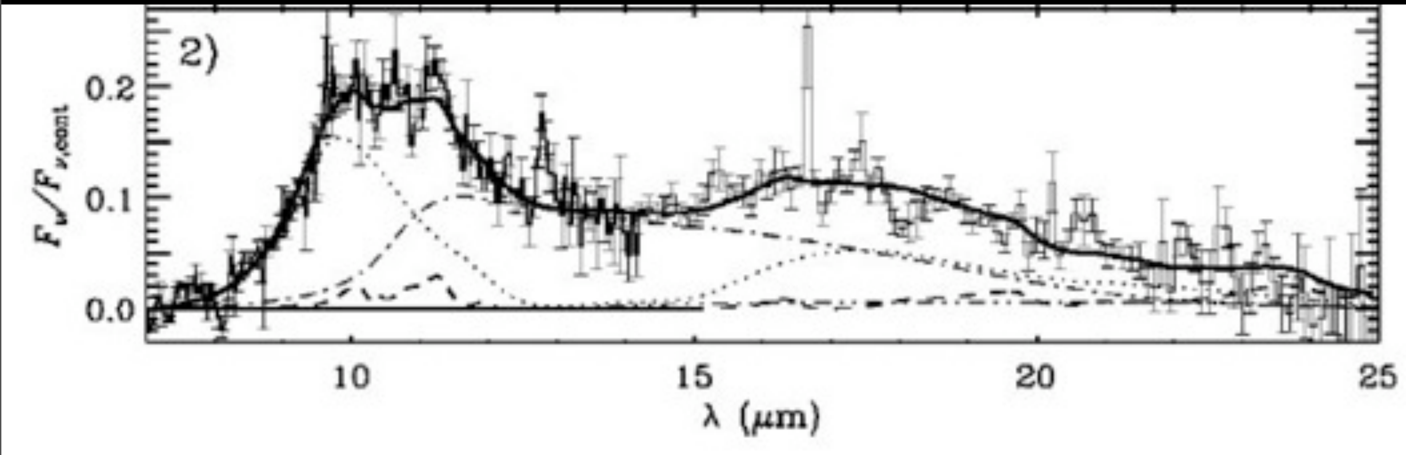
The First Clusters

- What is the structure of the first molecular clusters ?
- How does their formation depend on environment ?
- How does that influence the dust formation process ?

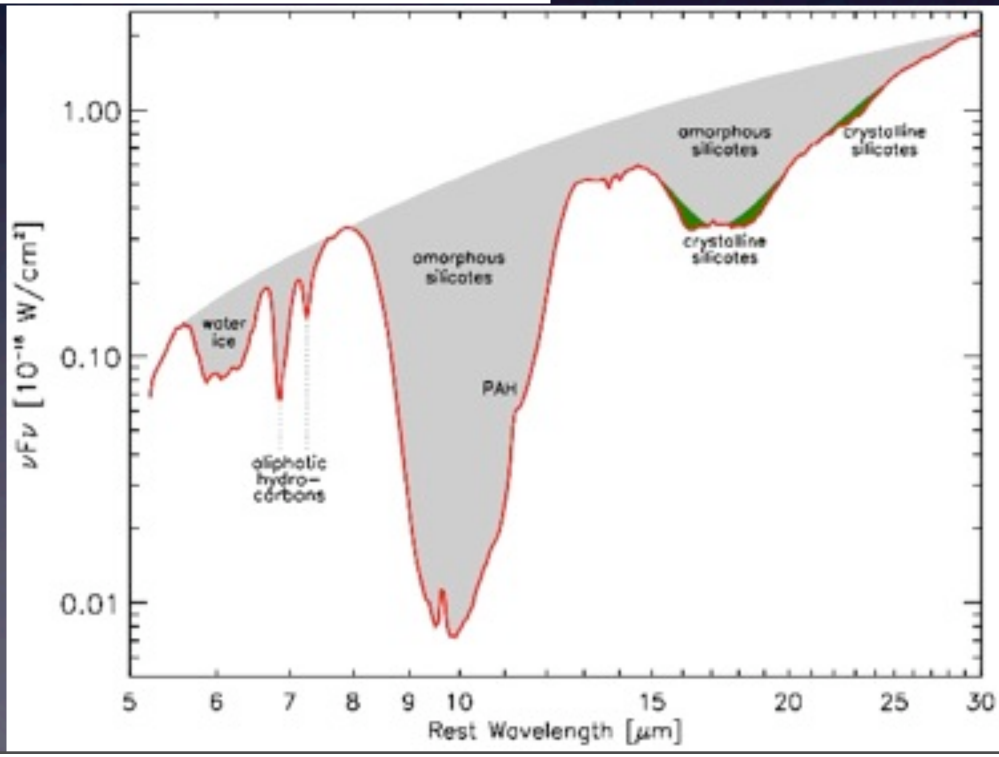


Ref: Cherchneff, Dwek, 2010, ApJ, 713, 1; Cherchneff et al, 2000, 357, 572; Cherchneff et al, 1992, ApJ, 401, 269; Frenklach and Feigelson, 1989, ApJ, 341, 372

Dust in Extreme Environments



SOFIA can probe stellar dust laboratories and relate the dust characteristics to the environment

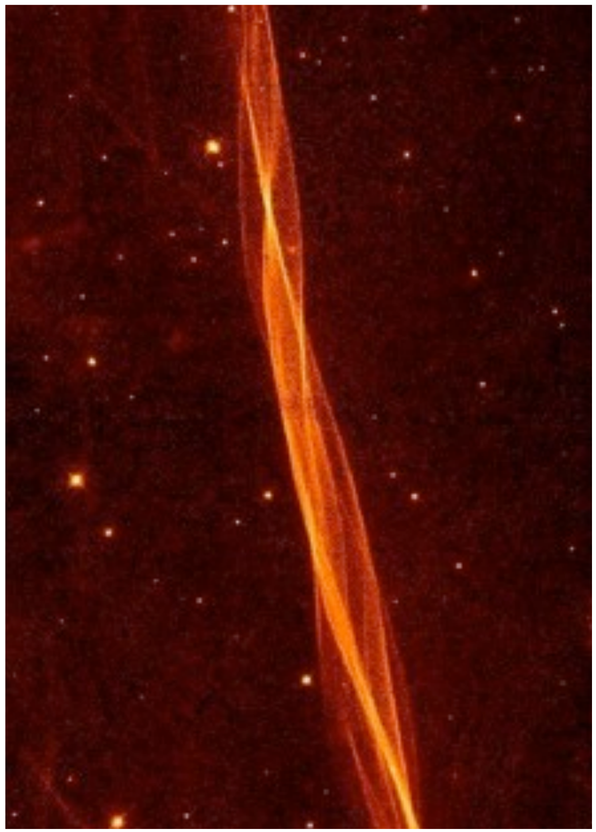


Ref: Marwick-Kemper et al, 2007,668, L107; Armus et al 2007, ApJ, 656, 148; Spoon et al, 2007, ApJ, 654, L49

Cosmic Journey of Dust:
3 Processing in the ISM

Dust & Interstellar Shocks

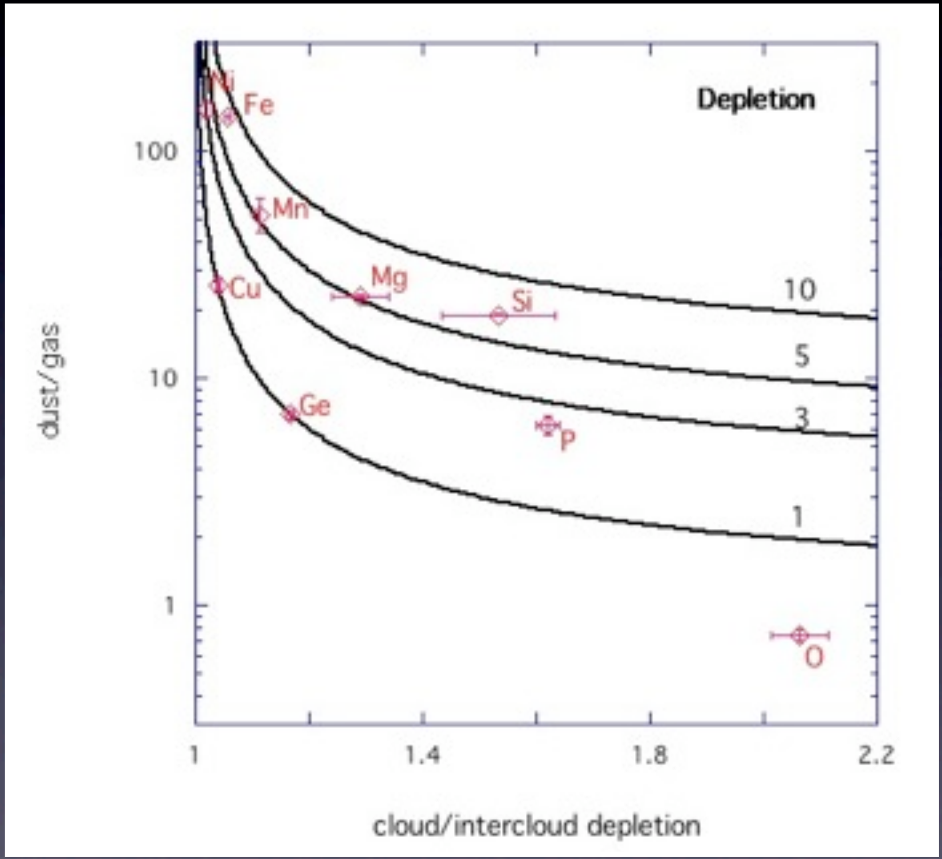
- Supernovae eject material at ~10,000 km/s
- This high velocity gas drives a strong shock wave, sweeping up interstellar material
- As the supernova remnant expands, the shock velocity will decrease until the swept up gas (and ejecta) merge with the interstellar medium
- Shocks destroy dust grains through sputtering and shattering
- 100km/s shock "chips" 30 Å layer from a 1000Å grain
- Calculated lifetime: ~500 Myr



Jones et al, 1994, ApJ, 433, 797

Shocks, Depletion & Grain Growth

- Depletion: elements are locked up in dust
- High velocity gas has less depletion
- Intercloud gas has less depletion than cloud gas
- Interstellar shocks in the intercloud medium sputter a thin outer layer (~30Å) which is rapidly reaccreted in diffuse clouds
- Carbon is not involved in these mantles
- Carbonaceous mantles from energetic processing of ices in molecular clouds or Solar nebula ??



Refs: Savage and Sembach, 1996, ARAA, 34, 279; Cartledge et al., 2006, ApJ, 641, 327; Tielens 1998, ApJ, 499, 267

Grain Growth

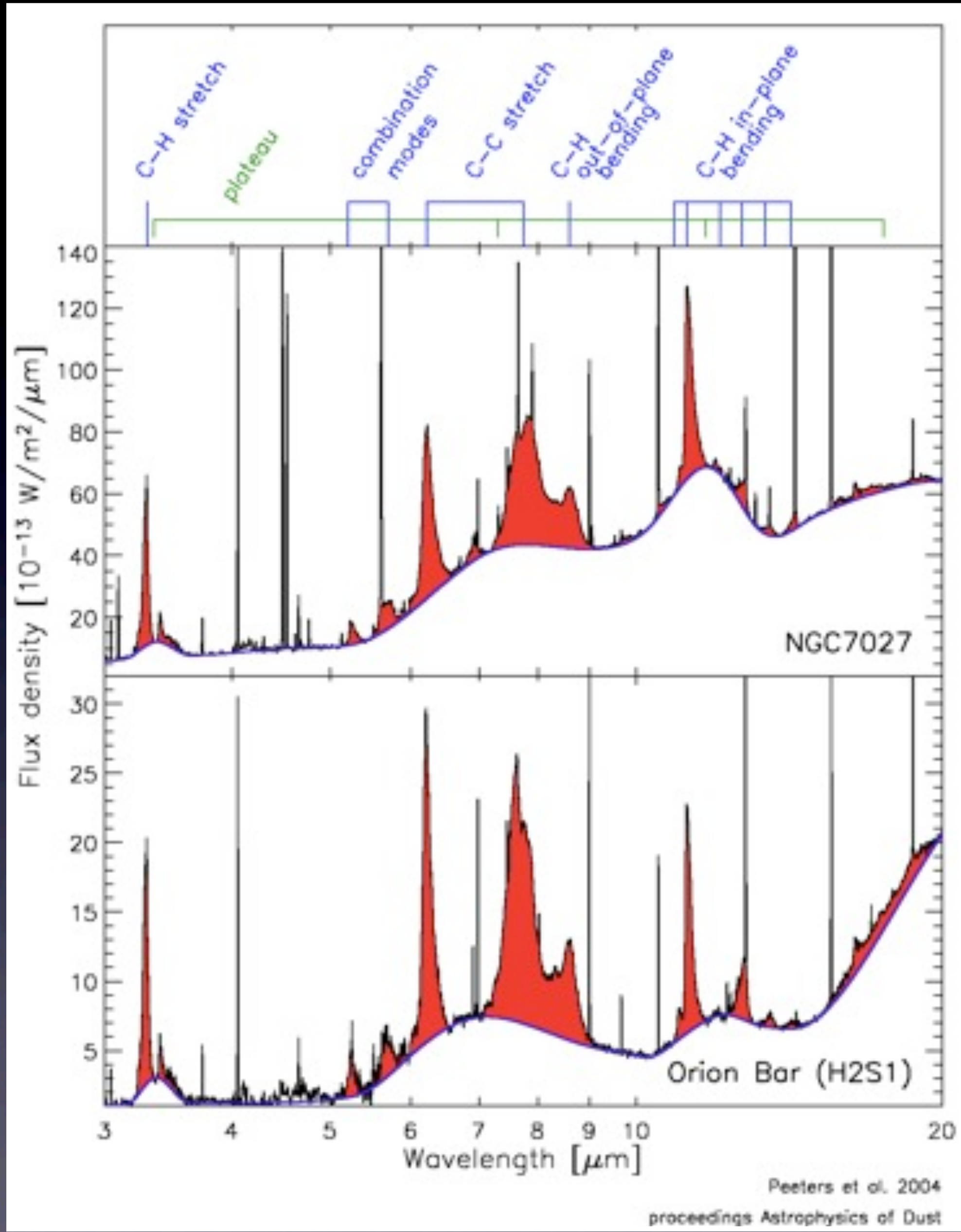
- Dust life time << injection time scale
- Grain growth is important
- Dust loses and reacquires thin veneer or is it 'completely' reformed ?
- Is interstellar dust dominated by stardust or by "mantled" dust ?

- Refs: Jones et al, 1994, ApJ, 433, 797; Dwek & Scalo, 1980, ApJ, 239, 193; Draine & Salpeter, 1979, ApJ, 231, 438

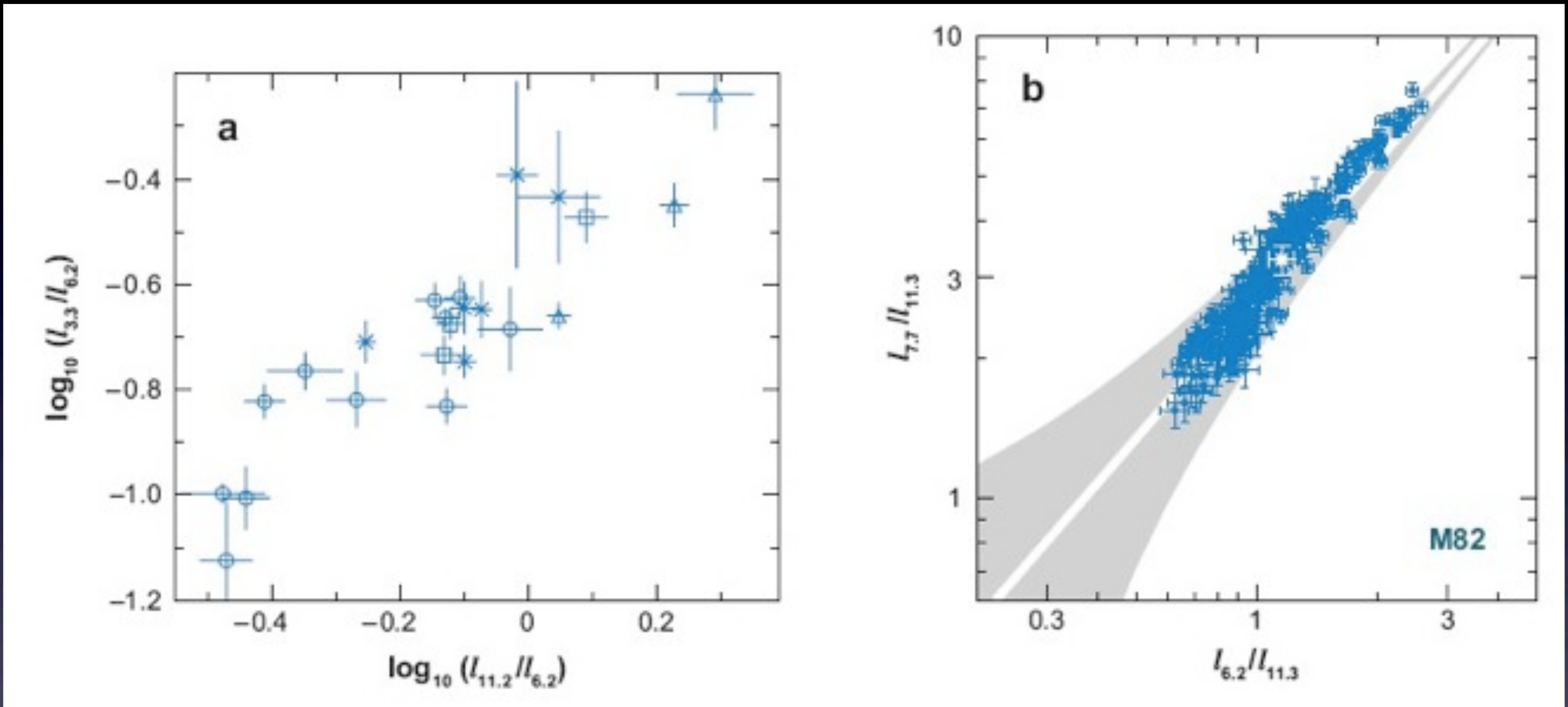
SOFIA can probe the relationship between stardust and interstellar dust

4 Interstellar PAHs

The incredibly rich spectrum of interstellar PAHs

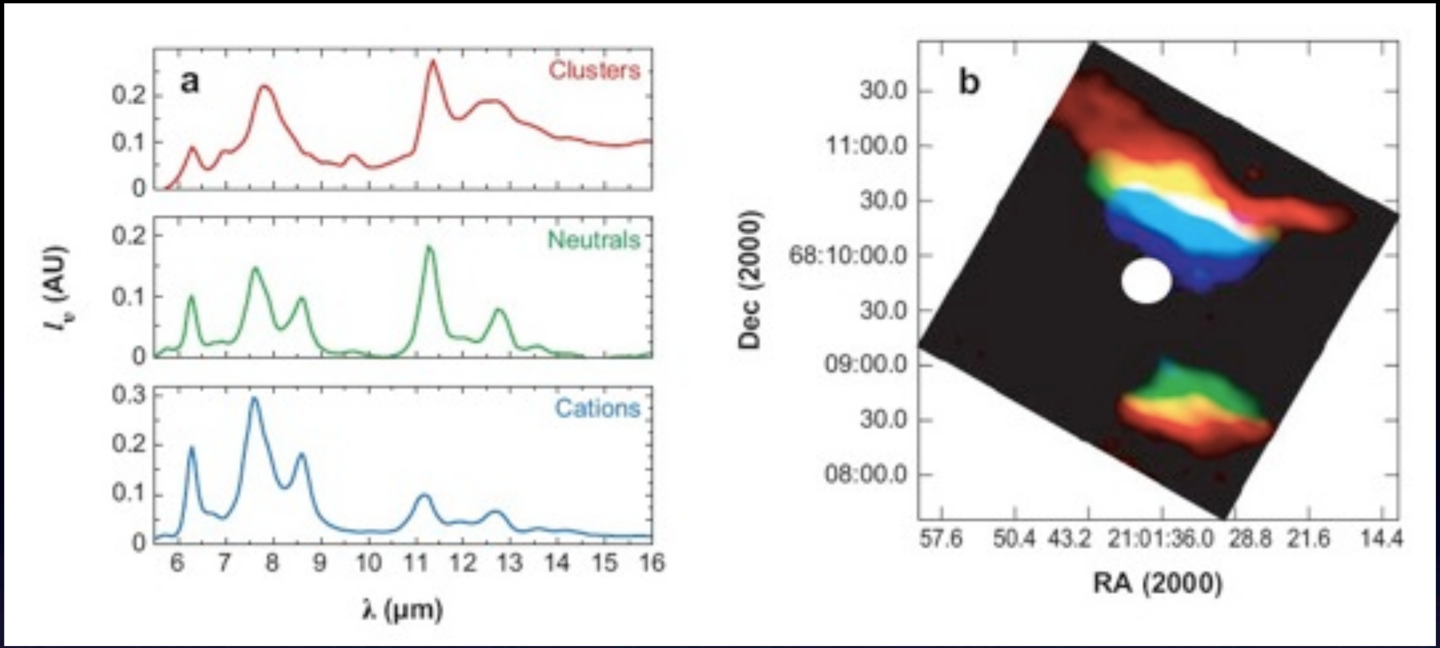


PAH Band Variations



- C-H and C-C modes vary independently

Refs: Galliano et al, 2008, ApJ, 679, 310; Hony et al., 2001, A & A, 370, 1030; Bakes et al., 2001, ApJ, 556, 501; Rapacioli et al, 2005, A&A, 429, 193; Berne et al, 2007, A&A, 469, 575



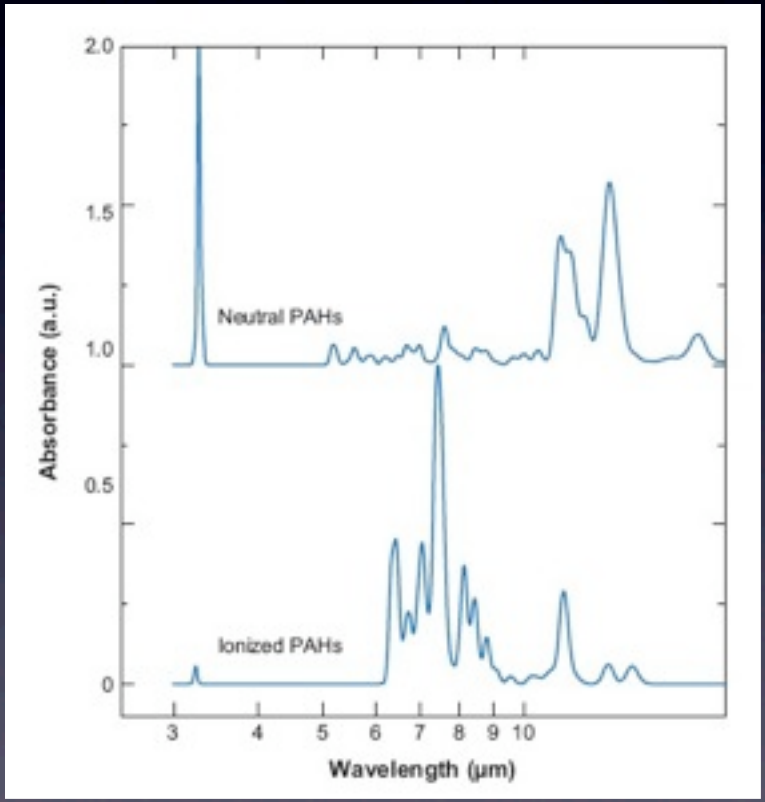
Blind Signal Separation & Principal Component Analysis methods

Refs: Berne et al., 2007, A&A, 469, 575; Raparciola et al, 2005, A&A, 429, 193

The Spectral Characteristics of PAHs

PAH spectra depend on:

- charge state
- size
- molecular structure
- clustering
- complexing
- heteroatoms
- temperature
- .....



Allamandola et al, 1999, ApJ, 511, L115

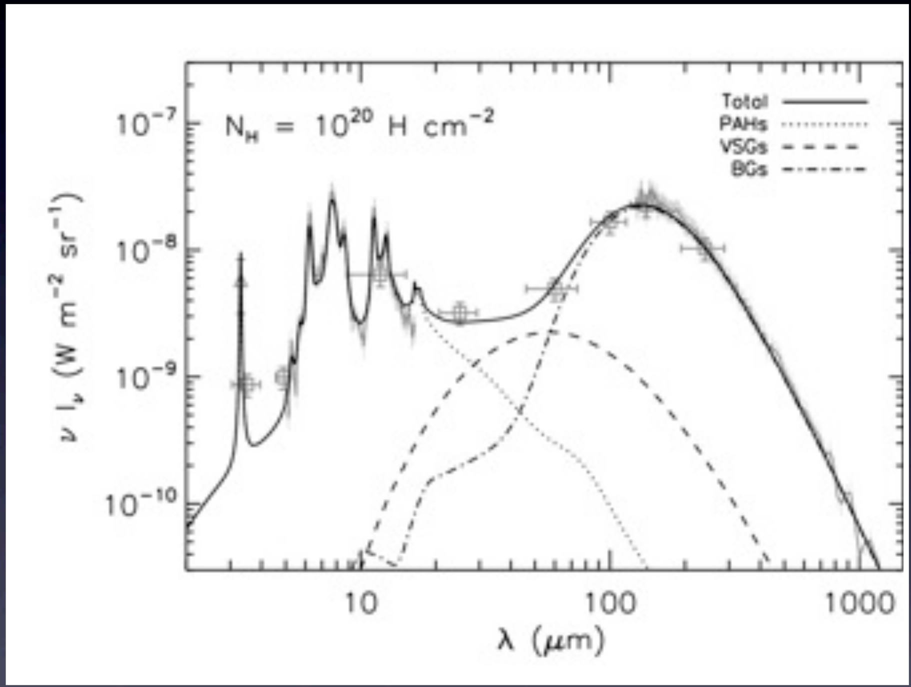
Langhoff, 1996, JPC, 100, 2819

Emission Components

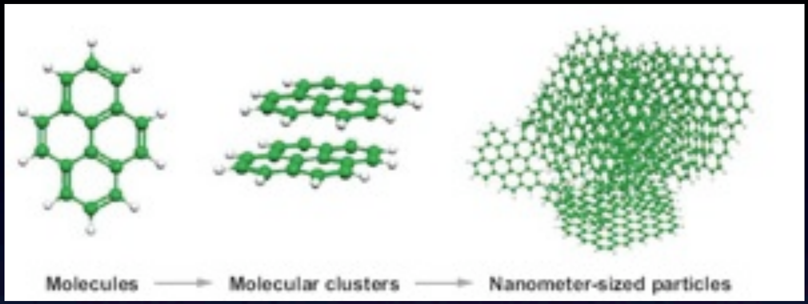
Emission components

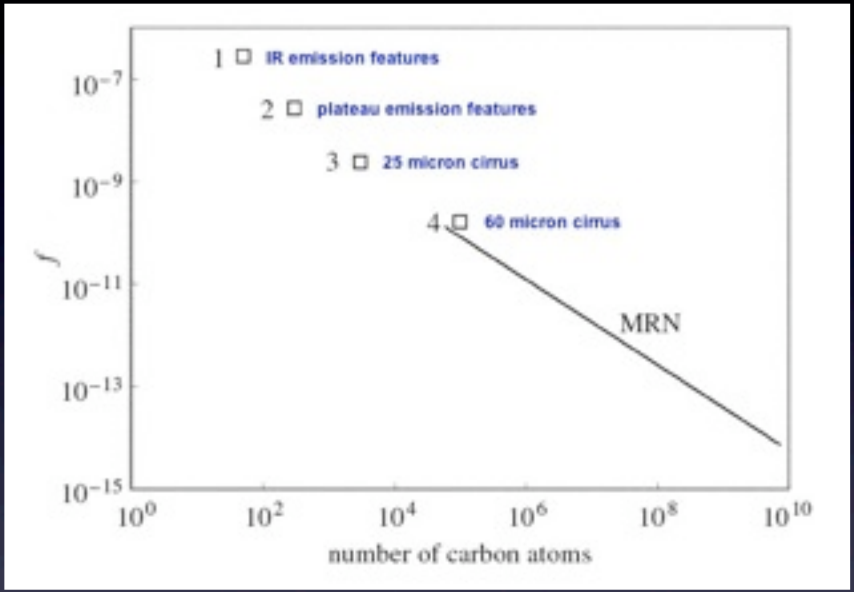
- PAHs (IR features)
- Clusters (plateaus)
- Very Small Grains (mid-IR Cirrus)
- Big Grains (far-IR continuum)

Models differ in the components and characteristics adopted



The Relationship of PAHs & Dust



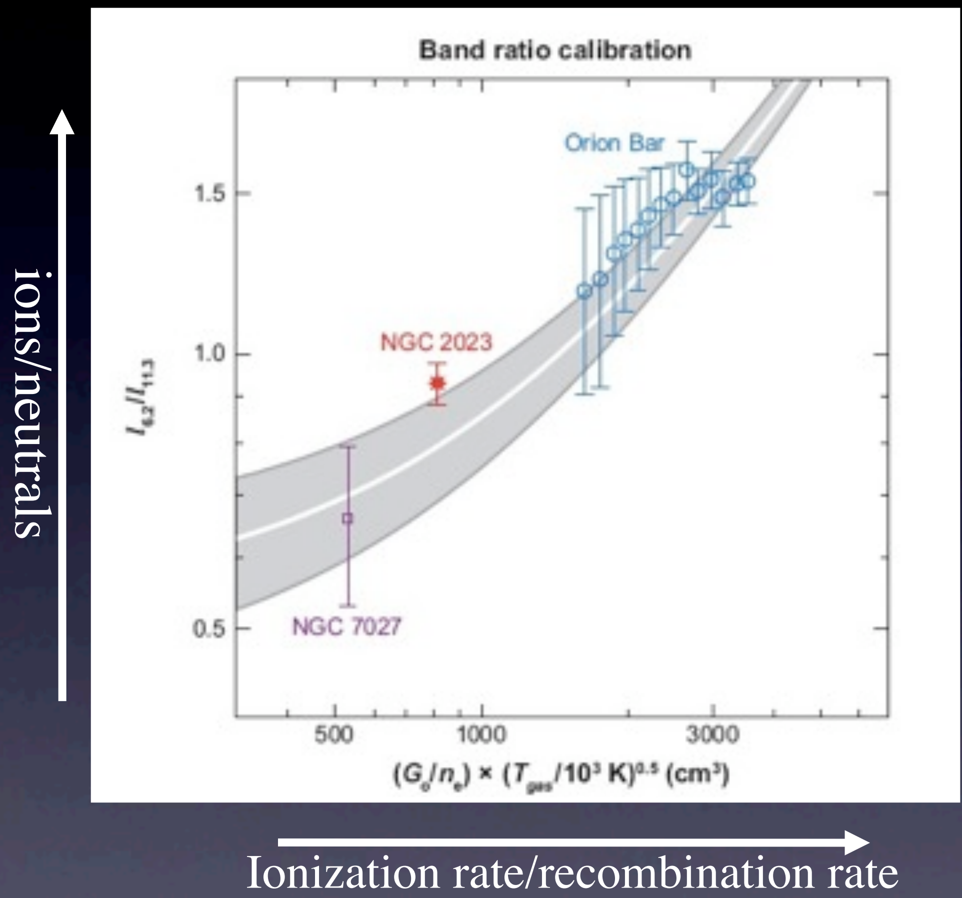


- PAHs are the extension of the interstellar grain size distribution into the molecular domain
- PAH/VSG/Dust grain abundance ratios vary with physical conditions/history

SOFIA can relate observed variations to local physical and chemical processes

PAH Ionization Balance

- Ratio of C-H/C-C modes measures charge state
- Calibrate PAH band ratios on well-studied PDRs
- Diagnostic atomic and molecular 'PDR' lines
- SOFIA can link the observed spectral characteristics of PAHs to the local physical and chemical characteristics



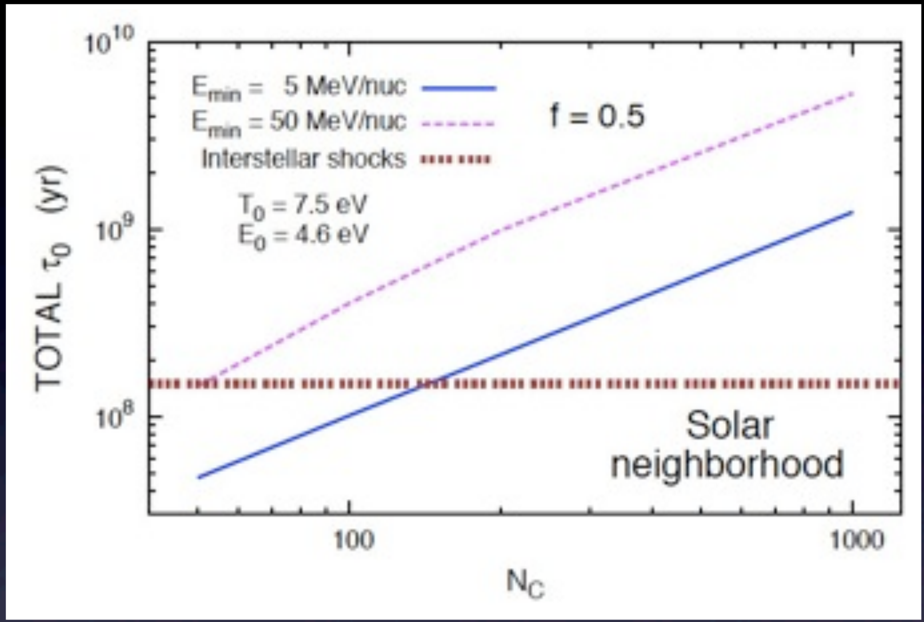
Refs: Galliano et al, 2008, ApJ, 679, 310; Hony et al., 2001, A&A, 370, 1030; Bakes et al., 2001, ApJ, 556, 501

The ISM is a Harsh Mistress

Lifecycle of Interstellar PAHs

Timescales estimated by extrapolating solid state concepts into the molecular domain

- Formation C-rich AGB stars
- Shocks/Cosmic Rays
    - Lifetime ~ 100 Myr
- UV lifetime 100 Myr
- Reaction rates are poorly known for large PAHs
- AGB star injection timescale ~ 2 Byr



Ref: Micelotta et al, 2010, A&A, 510, A36/37

Origin of Interstellar PAHs

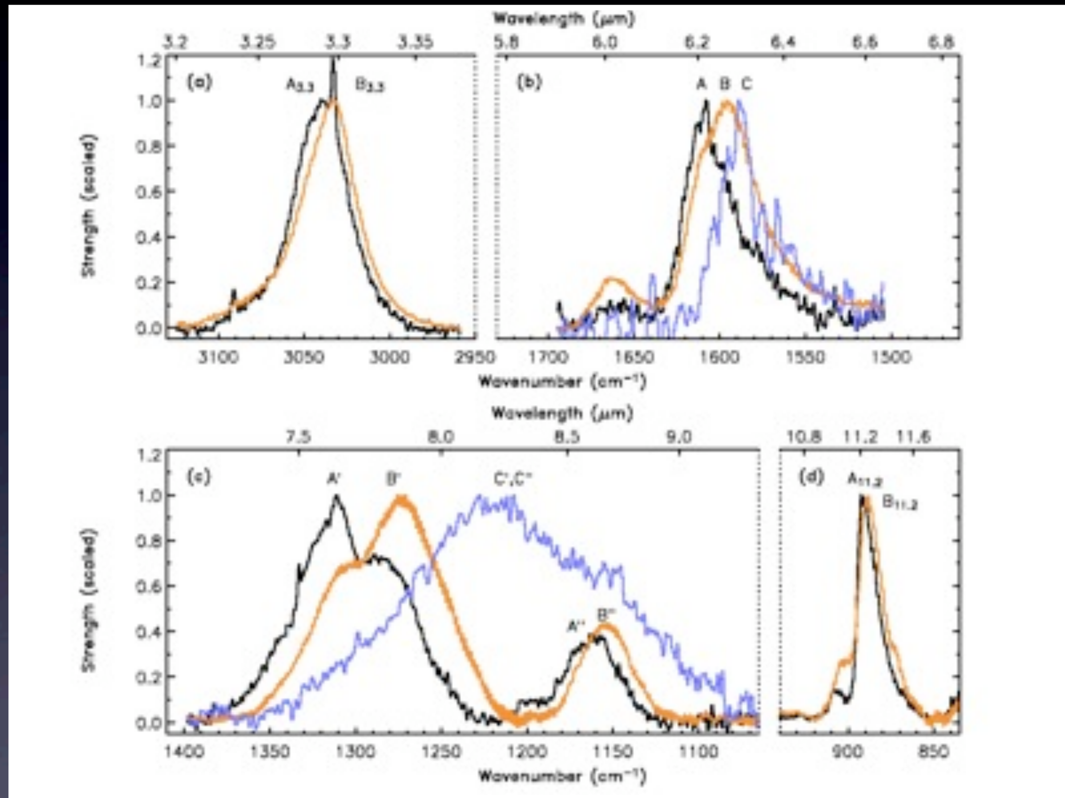
- PAH life time << injection time scale
- Are interstellar PAHs dominated by starPAHs or by interstellar PAHs ?
- PAHs as the leftover condensation nuclei in the soot formation route in stellar ejecta
- PAHs as the fragmentation products in grain-grain collisions in interstellar shocks

Refs: Jones et al, 1996, ApJ, 469, 740; Latter, 1991, ApJ, 377, 187

PAH Spectral Variations

Profile variations

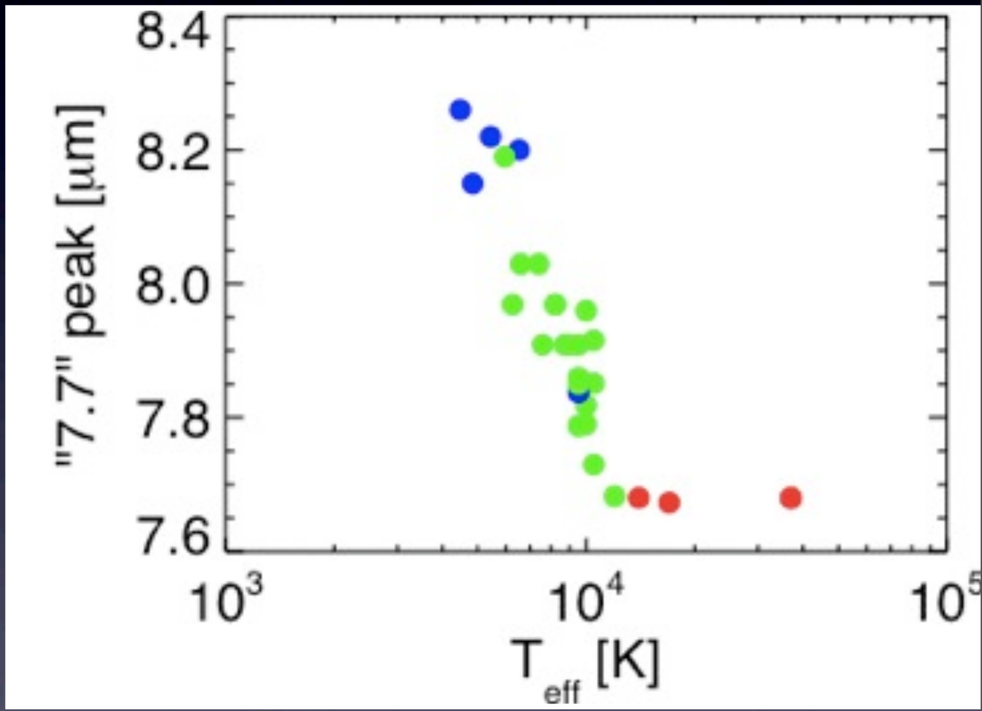
- Strongest for CC modes
- Classes A, B, C
- Classes correlate well for CC modes
- Correspond to object type



Peeters et al, 2002, A&A, 390, 1089

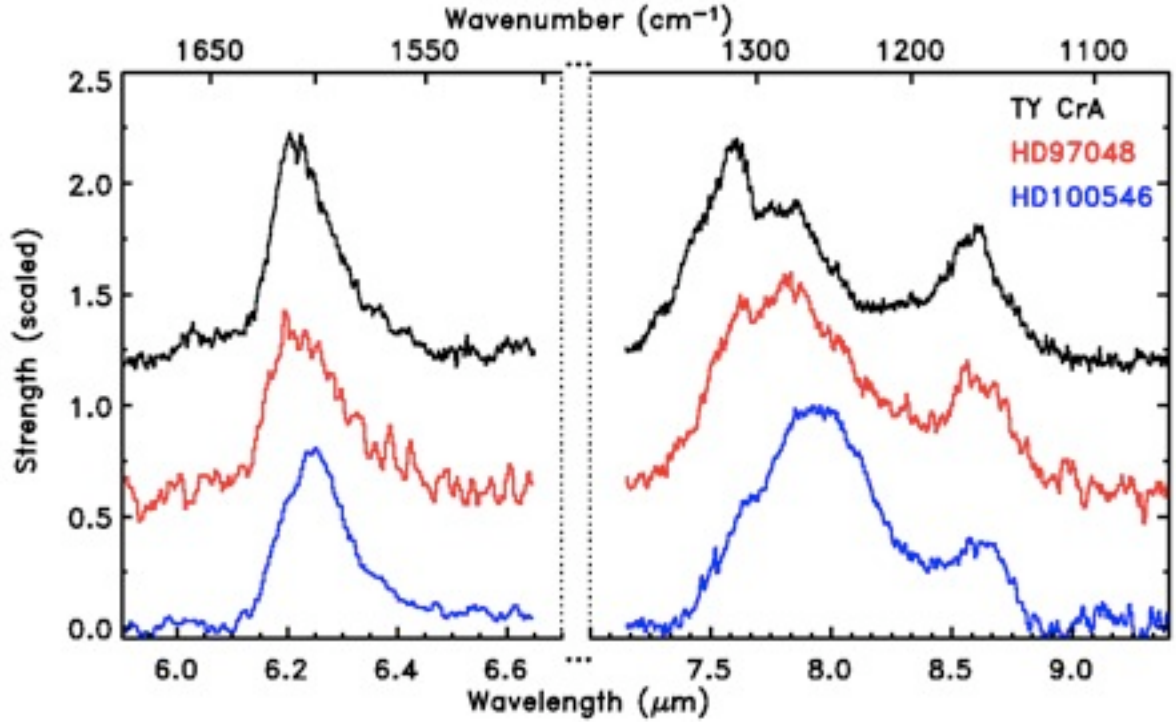
PAHs in Regions of Star Formation

- Peak position of the 7.7 μm band varies depending on source type
- Active chemistry



Refs: Sloan et al 2007, ApJ, 664, 1144
Boersma et al, 2008, A & A, 484, 241

PAHs and Herbig Stars



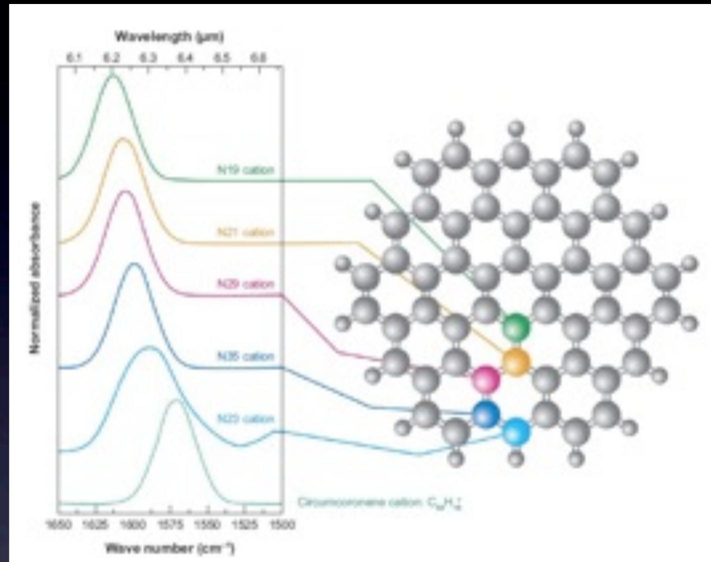
Source	Sp T	Size	Location
TY Cra	B7-B9	~2000 AU	HAeBe in cloud
HD 97048	B9-A0	~100-1000 AU	HAeBe cloud edge
HD 100546	B9	~150 AU	isolated HAeBe star

Ref: Boersma et al, 2008, A & A, 484, 241

Chemical Modification of PAHs

Origin of peak shifts

- N in the carbon skeleton
- PAH clusters (with Fe)
- PAH clusters
- Aliphatic/aromatic carbon variations

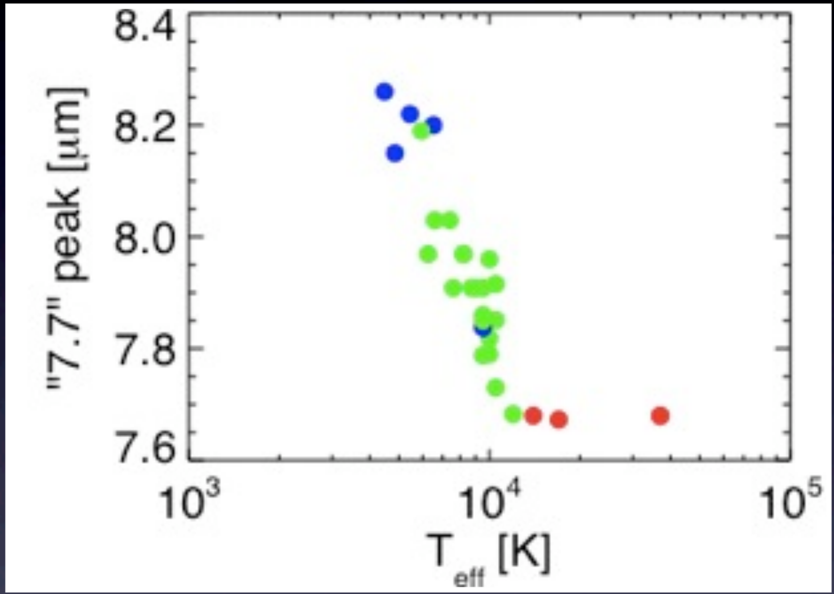


Refs: Peeters et al., 2002, A&A, 390, 1089; Pino et al, 2008, A&A, 490, 665; Rapacioli et al, 2006, A&A, 460, 519

JWST & PAHs in Planet Forming Disks

MIRI/JWST will be able to probe the spectral & chemical evolution of PAHs in regions of star and planet formation

- Chemical inventory
- Chemical processes:
  - UV/ X-ray/thermal
- Physical processes:
  - mixing/lightning/shocks



SOFIA – by probing a wide range of environments – can link observed spectral variations to the physical and chemical processes

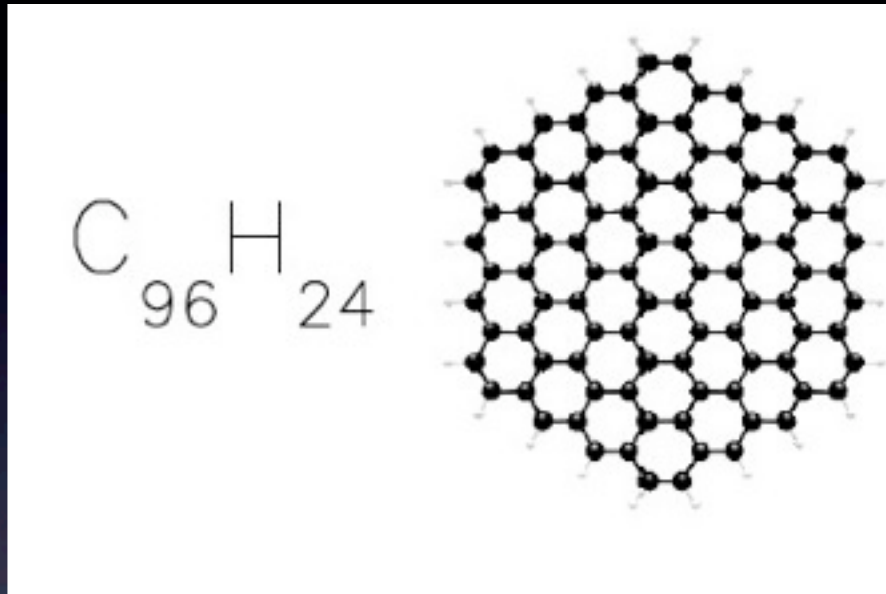
GrandPAHs

- IR emission spectra are very similar, particular in the "extreme" regions of the ISM

- 15-20 μm region often dominated by a few bands (16.4/17.4/17.0 μm)

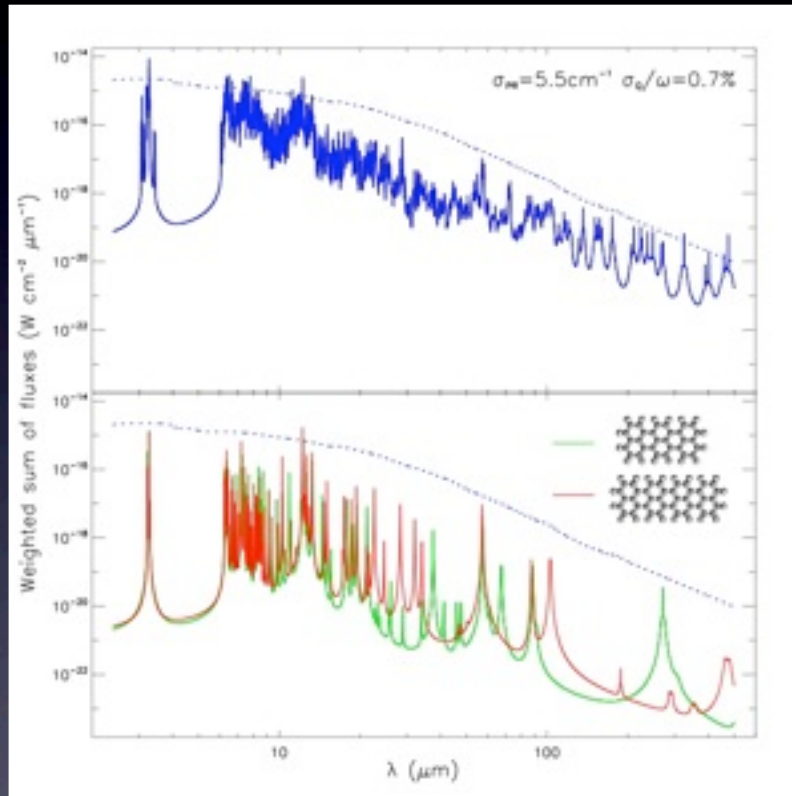
- Typical PAH will absorb some 100 Million UV photons over its lifetime ⟶ what can break, will break

- Interstellar PAH family dominated by a few, extremely stable species



SEARCHING FOR THE 'GRANDPAH'

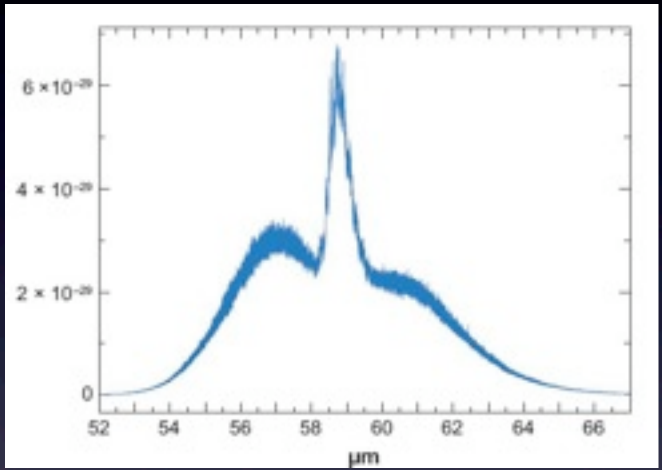
- The far-IR 'drum beat' modes are highly molecule specific
- Only SOFIA can measure all vibrational modes of interstellar PAHs
- Sample of objects with different conditions and different PAH family to probe chemical evolution and key processes

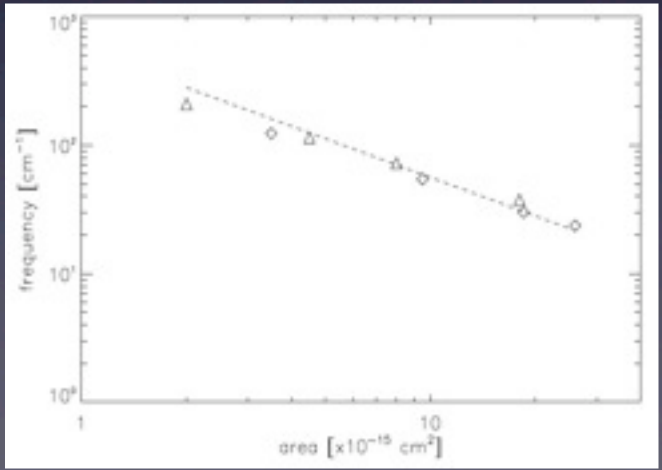


Looking for mr 'GrandPAH'

Identification of specific PAHs

- Drumhead modes: Lowest-lying vibrational state will emit when the modes have decoupled
- Observing strategy: search for Q-branch at moderate resolution over full spectral range
- Follow up with high resolution search for P/R branches
- SOFIA (& Herschel) can search for these signatures of the grandPAHs





Mulas et al, 2006, A & A, 456, 161; Boersma et al, 2010, in prep

Summary

- Infrared missions have provided us with an unprecedented view of the dusty & molecular Universe
- Most of the heavy elements are injected as “stardust” into the interstellar medium
- Space is a harsh mistress: Dust & PAHs are heavily processed in the ISM
- Undoubtedly, dust has strongly evolved over the lifetime of the universe as stellar populations change, star formation activity varies, and punctuated energetic events take their toll

PAHs & Dust in the Universe

- What are the characteristics of dust & PAHs injected by different stellar sources ?
- What is the contribution of low mass versus massive stars to the ISM budget ?
- How does this depend on metalicity and other galaxy characteristics ?
- How does this compare to the local interstellar dust characteristics ?
- What processes control the evolution of dust & PAHs in galaxies ?
- What does this imply for dust & PAHs in extreme environments ?

PAHs & Dust in the Universe

SOFIA's Niche:

- Mass inventory of stardust sources in the local Milky Way & comparison to interstellar dust
- Dust formation characteristics in stellar environments
- PAH characteristics and their relationship to the physics and chemistry of the environment

Building upon ISO & Spitzer and with contributions from Gaia, ALMA, & JWST

New Instrumentation

- Moderate resolution (R=300-1000) spectrometers covering from 3 to 300 microns
- Integral Field spectrometers (R=300-1000) in the mid-IR (3-20 micron)
- plus
  - High resolution spectrographs to probe the physics of the medium